ENERGY ANALYSIS OF LANDFORMS, SUCCESSION, AND RECLAMATION

by

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Energy models and evaluations were used to understand form and process in landscape systems. Embodied energy was used as a comparative measure of value for natural landforms, ecosystems, and human influences on landscapes.

Actual potential energy, embodied energy, and energy transformation ratios were calculated for ten landforms using energy analysis techniques and data from the literature. Included were floodplain, salt marsh, coral and oyster reefs, desert sand dune and arroyo, marine mud mound, ice-cored palsa mound, mountain glacier and spoil mounds formed by phosphate strip mining in central Florida. Energy transformation ratios were high, ranging from 10^6 solar Cal/Cal for a spoil mound to 10^{14} solar Cal/Cal for a coral reef.

Embodied energies of ecosystems overlying landforms were compared with those of landforms. Embodied energy is 10^9 to 10^{15} solar

Cal/m^2 for organization resulting from ecological succession and 10^6 to 10^8 solar Cal/m^2 for biomass. The difference between the embodied energy in biomass and that in successional organization is suggested as a measure of embodied energy in ecological complexity. There is up to 1000 times more energy embodied in this invisible structure than in biomass of the three ecosystems for which data are available.

Phosphate mining and reclamation were studied with ecological field measurements of succession, a simulation model of succession and energy evaluations. Data on succession were presented for a series of old spoil mounds ranging from 1 to 50 years postmining. Measurements included vegetation cover, optical density, litter weight and thickness, soil organic matter, number of ant nests, and tree height, density, basal area, and species composition. Patterns of development of the field parameters over time demonstrated that succession restored the mined land in a relatively short period.

For old mined lands that have not been reclaimed, a threshold age of 25 years was calculated beyond which more energy accumulated through succession than mechanical reclamation provided. Leveling of mounds in reclamation may divert a significant amount of energy rather than restore value.

A simulation model of succession was constructed and validated with litter measurements on the spoil mounds. In these simulations, succession was accelerated through the addition of seeds and litter so that a mature forest developed in 33 years rather than 50 years. Recommendations were given for managing succession as a more economical alternative to conventional reclamation.

CHAPTER 1
INTRODUCTION

Stretching across the continents of the earth is a seemingly endless variety of land types. Each individual area of land surface has a geomorphic form and an ecological system symbiotically coupled. Although sometimes separated for study, these features operate together in natural economies driven by the sun and other energy sources. The organization of these units is landscape, which is expressed as particular spatial arrangements or patterns. This is a study of the energy basis of various aspects of the landscape. Considered are energy theories of landscape along with classification and calculations of component land types. Models and energy analysis calculations are used to consider how landform, ecosystems, and land use by humanity may interact as a single system and to evaluate the amount of energy embodied in these systems.

A landscape model showing main energy storages and pathways is given in Figure 1. Using land as a platform, local energies such as sun, wind, rain, uplift, and others create form and ecosystems on any given area. These are long-term storages of landscape. Because these storages generate feedbacks to secure and amplify energy inputs, they have value. As noted by Odum (1975:147), geological structures of landforms "served as quality upgraded potential energy, information, and material storages that feed back control actions on the energy input processes."

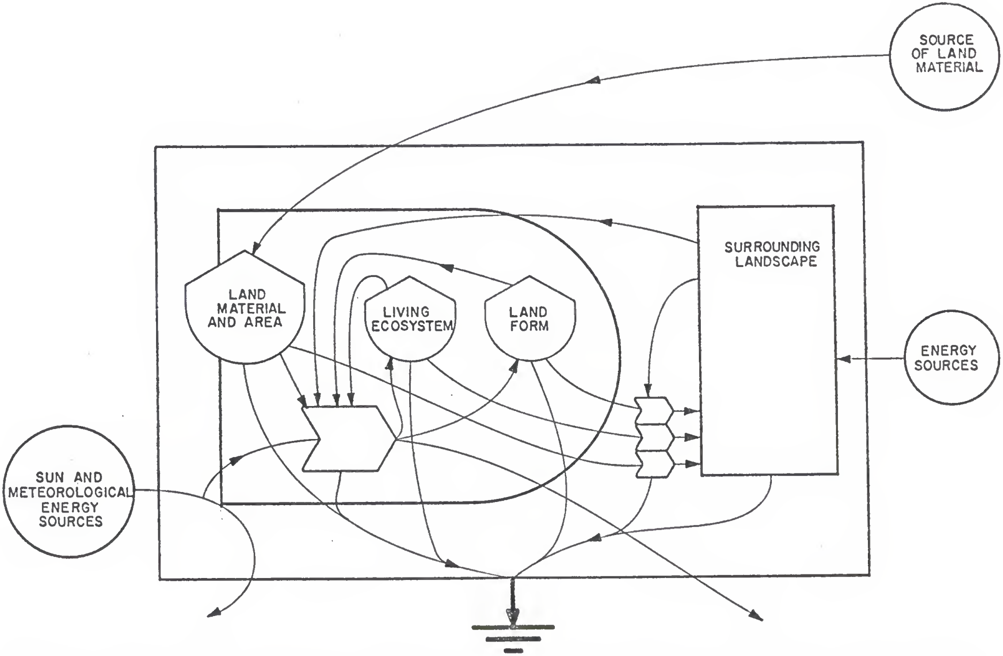


Figure 1. Energy model of a unit of land, showing principal storages of ecosystem and landform and connections with surrounding landscape. See Appendix 1 for a key to the symbols.

At one scale, landform is a consumer, causing a convergence of energies collected by surrounding land area. In return, the landform performs services such as organizing erosion and deposition, vegetation patterns, drainage, etc. Many individual land units such as shown in Figure 1 are combined into landscape by exchange with the surrounding systems mainly through flows of water, wind, seed, and animal movements. These flows integrate and organize the larger surface, generating properties of hierarchy in spatial dimension and feedback mechanisms that support self-maintaining stability.

Some of the actual stored energy in landform is potential against gravity, either to fill in for depression forms or to erode away for elevated forms. Other actual energy is stored in chemical concentrations of rocks, minerals, and sediments (Gilliland et al. 1978). Embodied energy in landform is the energy that was used to develop the form even though most of the actual energy used is no longer stored in the structure. Calculations of embodied energy stored in individual landform types were made by multiplying the total rate of energy used by the system by the equivalent basis of solar calories and by the length of time needed to develop internal storages.

Embodied energy of landforms may be related to effects of the form on the system. Can the amount of control exerted by the structure be inferred from its embodied energy? Control is shown in Figure 1 by the feedback from landform to the production process of the surrounding landscape. Calculations were made to determine which is more controlling, the living ecosystem or the nonliving landform.

In landscape dominated by humans, feedback from landform goes to farms, housing, and other land uses. What is the magnitude of control by landforms of natural and human landscapes? Does the embodied energy in landforms influence the locations of developments such as housing, utilities, waste disposal, etc.? Are there ways of making better use of landform energy for human economies?

In surface mining, feedback from landforms is interrupted, and entire landscapes can be totally disrupted, leaving new landforms and surfaces to be repaired by successional work of ecosystems and reclamation efforts by humans. Energy analysis was used to study phosphate mining and changes in landforms that result. What mining alternatives generate more useful landscapes? What reclamation designs best match the available energy inputs? How much energy is embodied in mining topography, and how does it compare with energy used for reclamation? Can succession be managed as a viable reclamation alternative? How do these conclusions affect recommendations for mining laws and techniques of reclamation? Models and energy measurements of phosphate mining in Florida were made to compare natural and human ways of managing landscape.

Previous Study

Energy and Landscape

The ancient Chinese art of geomantics was a system of landscape design principles and techniques used for siting developments. Partly scientific and partly magical, the goal of geomantics was "to produce a landscape which had to preserve certain spiritual values and also to fulfill the practical purpose of supporting a dense population" (Abercrombie 1947:30). The approach was to design with energy flows of earth spirits. Geomantics, known as Feng-Shui or literally "wind and water," attempted to read and influence the lines of flow of these energies by concentrating or dispersing them. Michell (1975:14) states, "as traditional Chinese medicine by acupuncture treats the human body by regulating the vital energy that flows through the skin, so the geomancer treats the body of the earth. Textbooks of Feng-Shui describe the nature of the telluric current, give examples of the energy patterns it forms in relation to different kinds of landscape and landscape features, and show ways of adapting its natural flow to human convenience."

More recent applications of energetics to landscape have been made in several contexts. Price (1947, 1955, 1959) was one of the first to recognize the importance of energy in the development of landforms. He developed a shoreline classification with five energy types: wave, current, river, tide, and sunlight (where organic systems dominate). Within the wave, current, and tide classes Price recognized at least two intensities, "zero" to low energy and medium to high energy. Tanner (1960a, 1960b) and Parker (1975) provide qualitative maps relating intensities of coastal energies to the resultant systems. Coastal ecological systems were classified according to characteristic energy sources by Odum et al. (1974). This classification included nearly 50 different kinds of ecosystems with special combinations of energies that generate them. The conclusion to be reached from these studies is that specific energy regimes cause or result in specific landform and ecosystem types.

The related concept of entropy has been used to explain the development of landscape properties such as longitudinal stream profiles and drainage network patterns. Leopold and Langbein (1962) explained the observation that rivers tend to have an equal distribution of energy degradation along their longitudinal profile by applying Prigogine's (1955) concept of systems trending toward a minimum rate of entropy generation. Since entropy generation is minimized they suggest that the work done by river systems also tends toward a minimum. Leopold and Langbein call this the "principle of least work." In a very different context, but still at the landscape level of organization, Zipf (1949) independently has developed a principle of least effort. This deals with distance minimization of human movements over highway networks. This principle is contrasted with the maximum power (or work) principle by Odum (1983) who notes that the minimum entropy concept only applies to low energy situations and that as available energy increases systems that survive tend to maximize rather than minimize useful work. In fact, the principles of least work do not seem to apply to the whole production process, rather only to the antecedent steps. Especially in terms of human movements, least effort as distance minimization is an important part of maximizing power, since it deals with bringing the factors of production together to initiate the production process. Jaynes (1979) proposed that landscape develops maximum entropy. Yang (1971a, 1976; Yang and Song 1979a) makes extensive use of a theory of minimum rate of energy dissipation derived from entropy concepts, similar to that of Leopold and Langbein (1962), to explain fluvial hydraulics and stream morphology. According to this theory "an alluvial channel is in an equilibrium condition if its rate of energy dissipation is at its minimum under the given climatic, hydrologic, hydraulic, geologic, and man-made constraints. The minimum value depends on the constraints applied to the system. If an alluvial channel deviates from its minimum value, it will adjust its velocity, slope, roughness, channel geometry, and pattern in such a manner that the rate of energy dissipation can be minimized to regain the equilibrium" (Yang and Song

1979b:56). Many derivations are given by Yang illustrating the theory including those showing that meanders (1971b) and pool and riffle sequences (1971c) are means for rivers to minimize the rate of energy dissipation. However, at least with meanders, the river may be subsidizing the floodplain forest ecosystem surrounding the channel to maximize energy flow by developing rich bottomland soils and spreading out water to increase its interaction with other energy flows. Forests growing under these conditions often have high gross primary productivity (Brown et al. 1979), which indicates maximum work. Apparently the question of when landscapes maximize and minimize flow requires more study. In another thermodynamic analogy Scheidegger (1970) substitutes elevation of land above baseline for temperature and land mass for heat storage, for use in gas laws and diffusion equations. These analogies allow derivation of characteristics of slopes and mountain ranges.

In other energy applications in geomorphology, Wolman and Miller (1960) suggest that for certain geomorphic forces, the greatest amount of work is accomplished by moderate events rather than infrequent catastrophies or frequent but insignificant events. Wolman and Gerson (1978) make a distinction between sediment transport work (quantity of material transported over a given distance in a given period of time) and landforming work or the actual sculpture of the landscape. They go on to discuss constraints on the geomorphic effectiveness of climatic events of various magnitudes and time intervals. Further support is given for the earlier statement that different kinds and amounts of work are done by different magnitudes and frequencies of forces. Carson and Kirkby (1972:72) provide a table of the orders of magnitude of geomporphic forces and their efficiency in transporting debris. Included are estimates for gravity, water flow, rainfall impact, and expansion forces due to changes in moisture, freezing, and temperature changes. They note "although very large amounts of thermal and biochemical energy are applied to the landscape, only minute amounts of these forces are actually effective in transporting debris." Water flow is suggested as the most important geomorphic force both in terms of energy expended and in amount of material transport. Systems diagrams of streams are given by Bull (1979) showing feedback relationships between variables that result in oscillations of sedimentation and erosion. Streams are viewed as sediment-transporting machines and are analyzed in terms of the availability of stream power to do work. This analysis centers around the concept of critical power threshold, which is the ratio of available stream power to the critical power needed to erode and transport sediments. Other geomorphology texts also include introductory chapters on energy as driving force (Crickmay 1974; Bloom 1978; Embleton and Whalley 1979).

Odum (1978a:14) presents a variety of energy interpretations of landscapes. He states that landscape is "the memory and the bank by which the flows of energy develop and maintain the capital against depreciation, and some for developing other values that go out in exchange for inflows." An outline of the method of calculating embodied energy in landform and other structures is given and is used in this study. The method is applied to a Florida cypress wetland and, converting energy units to dollars, a value of \$3837/acre·yr was found for this natural land type.

Energetics have also been applied to landscapes where man dominates over natural features as reviewed above. Energy principles, developed by H. T. Odum (1971, 1983), have been used for regional planning (Odum et al. 1975; Odum and Peterson 1972; Odum et al. 1979). Considered are topics of carrying capacity, investment attraction, predictions of future scenarios, and other topics. Applications have been made to south Florida (Odum and Brown 1979) and to many other counties, regions, states, and countries. Costanza (1975) drew maps of energy inputs (sun, wind, two kinds of rain energy, tides, waves, fossil fuels, and electricity) and of resultant structure (biomass, water storage, nutrients, and capital structure maintained by humans) in south Florida and found spatial correlation with economic development. The structure in landform was not evaluated, however, which might have improved the correlation between input energy and structure. Using the energy maps as a base, Costanza (1979) developed a spatial energy exchange model that generated patterns of development that approximated real landscape.

In other energy studies of human landscape, Woldenberg (1968) used the maximum entropy concept to investigate the nature of central place hierarchies. He attempts to explain this model of spatial organization with the steady state principle similar to the work of Leopold and Langbein (1962). The hexagonal lattice of central places is viewed as a least-work lattice, which represents the state of maximum possible entropy. A larger work (Woldenberg 1969) relates patterns of spatial structure to hierarchy in a variety of system including cities, rivers, trees, etc.

Odum and Kroodsma (1976) discuss a power park concept as a future landscape. Emphasis is placed on matching high energy—intensive land uses with larger areas of low energy—intensive land uses. Energy intensity of land use along with other design concepts have been discussed by the Southwest Florida Planning Team (1972).

Grillo (1960) attempts to generalize geometric form into two classes: a cracking pattern as an expression of potential energy and an erosion pattern as an expression of kinetic energy. Examples are taken from landscape, art, and urban design.

Reclamation

In the past, around the turn of the century, reclamation meant bringing a "wasteland," such as flood-prone lands and deserts, into economic production. Existence of naturally produced value was often overlooked. At that time there was a National Bureau of Reclamation in U.S. government. The meaning of reclamation is different now. Reclamation involves the repair of a disturbed site, returning the value lost in disturbance. Reclamation is sometimes defined in the general sense of replacing any system that has value and is contrasted with restoration that is taken to mean replacement with a system that is equivalent to the original system that existed before disturbance. No such distinction is made in this study and reclamation and restoration were used interchangeably.

Surface mining and erosion of agricultural land are two of the more common terrestrial disturbances requiring reclamation. Terrestrial reclamation often consists of the following: land grading and manipulation, soil preparation, fertilization, irrigation, erosion control, and seeding and planting. The task is essentially one of establishing an ecosystem that will provide a cover over disturbed areas in the least amount of time. Although natural succession will usually restore an area, reclamation is invoked to speed this inherently slow process. Costs can be as high as shown in Table 1. The least cost proposed is $300/acre for a Florida pasture and the greatest is about $300,000/acre for a mangrove

Table 1. A comparison of the costs of reclamation projects.

Restored Ecosystem	Type of Disturbance	Location	Cost $/Acre	Reference
Semi-arid shrub and woodland	Oil shale mining	S. Colorado	1,320	Heley and Kilburn 1973
Woodland	Coal mining	Bridgeport, WV	3,367—4,374	Grim and Hill 1974
Arid shrub land	Copper mining	Tuscon, AR	1,298	Ludeke 1972
Beach dune	Construction, trampling	Atlantic Coast, FL	400	Davis 1975
Mangrove forest	Oil spill	Puerto Rico	308,209	Torruellas 1978 (cited in Lugo and Brinson 1978)
Pasture	Phosphate mining	Central Florida	300—600	Wang et al. 1974

forest in Puerto Rico. Where succession is allowed to restore the land there are no direct costs. Productivity lost during disruption is often omitted from reclamation accounts. Often the costs of reclamation appear to be exorbitant and their economic value is questioned (Singer 1977). Partly because of lack of knowledge about succession on disturbed sites, use of succession as a reclamation alternative is uncertain, and costs involved are unknown. In this dissertation, objective techniques of energy analysis were used to consider reclamation alternatives in phosphate mining in Florida.

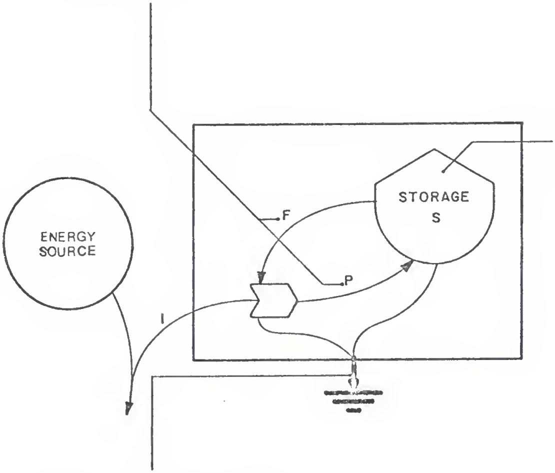
Background and Concepts

In sections that follow, concepts, hypotheses, and definitions are given for relating energy to landscape forms and storages. The energy measures defined here were evaluated in the research on theories of landform development.

Energy Storage Value of Landforms

In these studies storage of landforms was assigned three energy-related values: actual potential energy content given in Calorie equivalents, embodied energy given in solar equivalent Calories, and energy effects given as the ratio of effect to feedback. These values are compared in Figure 2. The actual energy stored is that found by converting it entirely to heat. This is not a measure of work or effect because energies are usually used in systems in amplifying interactions with other energy flows rather than being degraded into heat without interaction. The same actual calories of different types of energy, such as solar, fossil fuel, and electricity, will not amplify the same amount of

Energy Amplifier Effect is the Ratio of Amplified Production Flow P to Actual Calories of Feedback Flow F



Actual Potential Energy Content (Actual Stored Calories)

Embodied Energy of Storage is Sum of Energy Used of Quality S to Develop Storage Over Time

Figure 2. Model showing different energy values of storage.

productive work. This is another way of saying that different energy types have different qualities.

Embodied energy is one measure of energy quality. This has been defined as "the energy used in developing energy of higher quality" (Odum and Odum 1980). It is the amount of one type of energy used to make another type. Embodied energy storage is the total energy equivalents of one type used over the time needed for development of the storage. This meaning is similar to the economic notion of capital cost.

Energy multiplier effect is another measure of the quality of energy as its effect or "release" value. Ideally this is the amount of energy it can release or amplify in a process involving interaction with other energy flows. This is difficult to estimate since many energies feed back and forward in complex webs of converging and diverging flow, and individual effects can not be separated easily. It might be expected that embodied energy is correlated with energy effect ("energy cost" = "energy effect"), but such relationships have not been tested. In this dissertation, attempts are made to quantify these energy measures of value for storage in landforms under a diversity of different climatic regimes and vegetational influences.

Though not often considered as such, the form of land is a long-term storage. Odum (1975:147) states, "geomorphological form and information as measured by capital energy investment becomes as much a state variable as biomass in biology or water in hydrology." The actual storage value of landform is its heat content. Geomorphic forms are either depressions, like lakes and wetlands, or elevations, like mounds and hills. Their actual potential energy content can be estimated as potential energy stored against gravity, either to fill in for depression forms or to erode away for elevated forms. Other potential energy may be in chemical substances of the storages.

Embodied energy of a landform is the energy used, in equivalents of one type, multiplied by the development time. This approach to quantifying embodied energy assumes that a production process is competitive so that for any given landform development time has been minimized through the interaction of the ecosystem with the energy sources. In this sense natural selection may operate on the non-living landform directly through the living ecosystem.

Several problems are involved with estimating the energy in landform, or any other long-term storage, such as biomass, which is made up of cumulative additions over time. Eight algorithms for predicting total energy used by a system have been proposed based on the inflows of energies (Odum 1983). No one method is apparently most appropriate. In this study, energy used in developing landform was calculated as the solar energy embodied in wind, rain, river, waves, tides, and other energies. This approach avoids double counting of sunlight from which most other natural energies are derived from biospheric cycles.

Criteria for choosing the point in time when development ends, in order to calculate embodied energy, are not clear. Some parameters may continue to develop after others have stopped; for example, in a forest the diversity of species may continue growing after biomass has reached steady state. Moreover, does energy keep becoming embodied even after a steady state is reached with long-range slow changes in biological evolution? For the purposes of calculations here, the age of a landform was used as development time and, for ecosystems, the length of time from initiation of succession until climax is reached. Climax was used as a period when main storages were little changing.

Energy effect of landform is the amount of control exerted over landscape processes. One approach to quantifying energy effect is to measure power use when storages are being utilized without replacement. For elevated landforms this is the erosion rate and for depression landforms it is the deposition rate. If not continually renewed, both of these rates represent loss of volume of storage. The landform is actually degraded by these processes, which represents work that yields energy effect.

The development of natural vegetation patterns serves to control erosion and deposition in undisturbed conditions. Human occupation of landscapes, however, generally converts natural vegetation to other uses, arrests succession or substitutes less mature vegetation such as agriculture and lawns. The effect is often accelerated erosion in one area accompanied by deposition elsewhere. Man's overall impact in consumptive use may be the leveling of landscape to more even surfaces. This may not be the best use of landform energy unless the cycle of growth and development maximizes power in the long run. Odum (1972) cites a similar example showing growing human populations drawing on large ancient geochemical storages that were adapted to biosphere cycles as a step to start a new system of industrial man.

Hierarchy in Landscape

In relating energy to area, a hierarchy of storages develops to maximize useful work. Landform hierarchies are maintained by convergences over large areas, not just by energy over individual structures. Analogous with food chains of species populations within ecosystems, landscapes may be considered as "food chains" of landforms in spatial dimension. Dilute, undifferentiated expanses capture the main energy flow and focus or concentrate it into structured landscape systems. In response to the concentrating flows, the landform may redistribute high quality services back to the surrounding system. General aspects of energy distributions in hierarchy are described and explained by Odum (1983) and Brown (1980). In this dissertation, spatial hierarchies of landform are considered.

Energy convergence in landscape may be roughly proportional to the ratio of areas of different type. Each high quality landform has a collection area contributing energy to it through water flows and other convergent pathways. More area allows more development of the hierarchy to be supported. Recognizing the hierarchical ratio of one land use to another helps estimate embodied energies where pathways converge. For example, Horton (1945) proposed a hierarchical relationship between the relative position of a stream, in a drainage basin (stream order), and the log of number of streams called the law of stream numbers. This shows a basin with many small streams of low order converging energy to progressively fewer streams of higher order.

Spatial Expression of Energy Sources

Landscape patterns of hierarchy depend on the spatial distribution of energy sources. Odum (1983) gives three types similar to those described below. Also a fourth is included here. Figure 3 is a representation of four basic spatial distributions that energy inputs can take—sheets, points, fronts, and lines. All of the spatial energy distributions act synoptically over relatively large areas as a moving force.

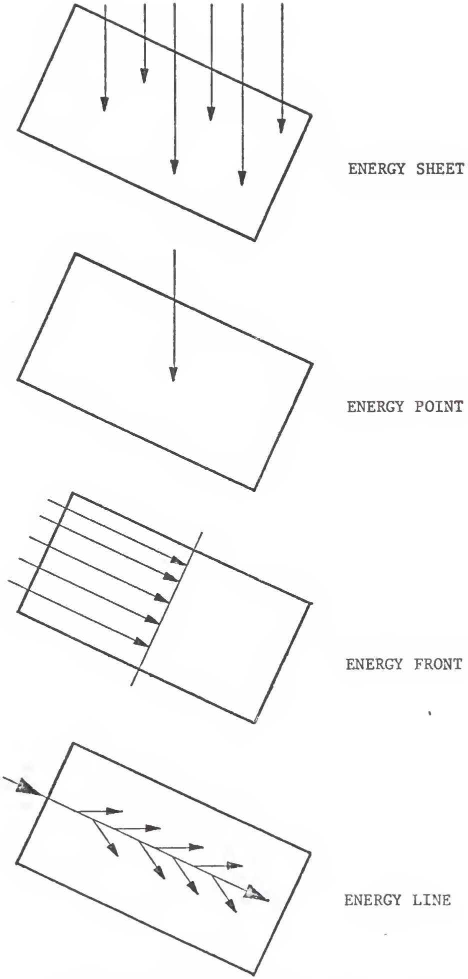


Figure 3. Diagrammatic representations of four basic types of spatial energy distributions. Arrow points show where potential energy is delivered.

Energy sheets are those delivered over a broad area perpendicular to the surface. Sunlight and rainfall are examples of an energy sheet from above the surface. A potentiometric surface of groundwater and a uniform rock substrate emerging from an uplift process are examples of a sheet incoming from below the surface.

An energy point also is delivered perpendicular to the surface but at one point such as an artesian spring rather than over a broad area as in the case of the sheet.

An energy front is defined as a source that delivers energy along an edge that moves parallel to the surface and sweeps across the landscape. Examples are weather fronts, sheet flows, runoff, and tides. These energies act as the line of the front passes.

Energy lines deliver energy along a line parallel to the land surface. Energy is supplied by force along the line and at the end point of delivery. Like energy points the line force is expressed over a small area. Rivers and electric power lines are examples of energy lines.

Table 2 categorizes many natural energies into the classification scheme of spatial expression of energy sources.

Defining an Energy Source

Each energy source also has a time program including frequency, intensity, duration, and direction. To fully describe an energy source then requires specification of

a. actual heat equivalents and/or physical units;

b. energy type and its embodied energy flow expressed in units of that type;

c. spatial distribution of energy delivery; and

d. program of delivery with time.

Table 2. Examples of some energy sources classified by spatial types.

Sheets	Points	Fronts	Lines
Sunlight	Artesian springs	Cold front	Rivers
Chemical potential of rain	Volcanoes	Runoff	Tidal jet
Nutrients in rain or rocks	Mineral deposit (intrusion, intruding)	Tidal bore	Glacier flow
Kinetic impact of rain	Sink holes in limestone	Waves	
Uplift of land			
Rise of water tables			

Plan of Study

Energy basis of landforms was evaluated including those that are part of natural landscapes and those part of landscapes of human economic development. Quantitative evaluations of embodied energy were made as a measure of landscape control and value. An energy signature of interacting energy inflows was calculated for ten landforms. For each a minimodel was constructed of the landscape structure and its interaction with the input energies. Actual energy in landform was calculated with various potential energy equations. Embodied energy in storages was found by multiplying the energy signature used over the support area by the energy transformation ratios and the development time. Embodied energy of vegetational components was also calculated and compared with landform values. Embodied energy of landscape was related to location of human developments and to aesthetics.

The theory that spatial expressions of energy sources control patterns of landscape was tested for four cases. Landscape pattern was used to predict dominant energy, which was then calculated independently. A classification of the shapes of landforms is presented, and the adaptive value of shape in absorbing energy flows is discussed.

The energetics of developing a human-dominated landscape was studied, using the phosphate mining district of central Florida as an example. Relative values of human and natural landscape work flows were compared. Energy in strip mining topography was evaluated and compared with natural landforms. Ecosystem development on spoil mounds was investigated by measuring characteristics of successional systems on mounds of different age, ranging from 1 to 50 years since mining. Forest structure and composition on the oldest spoil mounds were compared with a mature undisturbed forest to assess the degree to which succession has naturally restored development. A model of succession was constructed for southern coastal plains old field succession and validated with data from spoil mound succession. Simulations tested alternatives for accelerating succession. Energy analysis was used to evaluate mechanical reclamation versus natural succession as alternatives. A model of a typical fertilizer operation was constructed to place reclamation costs in perspective of whole industry budgets and to calculate net energy of phosphorus. Recommendations based on fieldwork and model simulation were made for effective ecosystem restoration on disturbed lands.

Site Description

Phosphate Mine Study Sites

The study sites for fieldwork on successional phosphate mine ecosystems were located in southern Polk County in the central Florida phosphate district (Fig. 4a). Eight sites were studied ranging from 1 year to 50 years in age. All sites but one were located at the Payne Creek mine of the Agrico Chemical Company (Fig. 4b). The remaining site (50 year) was about 16 kilometers north of the Payne Creek mine in the Christina residential development of the International Minerals and Chemical Development Corporation. Study site ages were determined by a review of mining records on file at the Agrico Chemical Company office and by discussion with mining officials. All sites were abandoned mine areas dominated by rows of spoil mounds or plateaus. The mounds were formed of overburden materials (sands) stripped and deposited by the operation of dredges or drag-

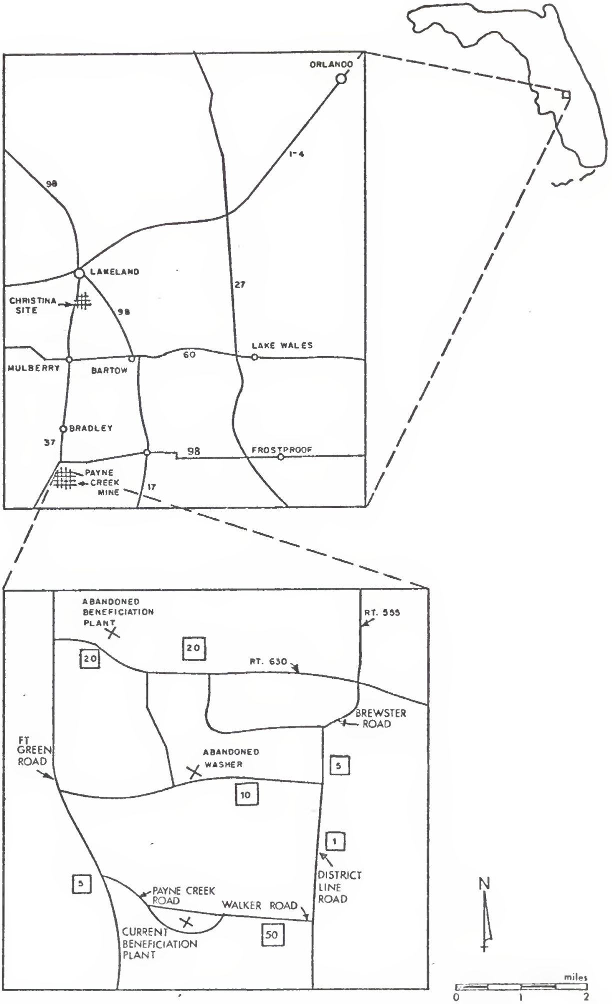


Figure 4. Location of phosphate study areas: (a) central Florida phosphate district showing main study areas at Christina and Payne Creek; (b) location of successional study sites on the Payne Creek Mine (numbers refer to the age of the site in years since mining).

lines. Mound heights ranged from 3 to 12 meters. Data were reported by age of the mound. Where two sites of the same age were studied, their data were averaged.

The 50-year-old sites differ significantly in geomorphology from the younger sites. At these older sites spoil material was deposited in blocks as large plateaus rather than in the more recent configuration of spoil mound rows with intervening troughs. So as to minimize the effect of the differences in original spoil shape, only the slopes of all areas were studied.

Sites in San Felasco Hammock

In order to assess the degree to which natural succession restores ecosystem structure, the mesic hammock forest on the San Felasco Preserve was sampled and compared to the oldest ecosystems on spoil mounds. San Felasco is a mature or late successional forest and was used as a "climax analog" to compare with phosphate succession. The forest is located about 13 kilometers northwest of Gainesville in north-central Florida off State Road 232. It is in a protected area of state preserve associated with a large sink hole, the Devil's Millhopper. Many ecological studies have been conducted on this forest including aspects of vegetation (Monk 1960), light transmittance (Ewel 1969), mineral cycling (Ewel et al. 1975), and metabolism (Lugo et al. 1978). The sampling site used in this study was a shallow slope with moist soil and many evergreen species. Although San Felasco Hammock is approximately 200 kilometers north of the central Florida phosphate region, the vegetation is to some extent similar and comparisons were thought to be useful.

Landform Sites for Embodied Energy Calculations

Table 3 lists the landform types chosen, their location, and special adaptations. Examples were picked to cover a variety of environments with different dominant forcing functions. Comparisons were then made between arid-humid types, boreal-tropical types, and across multitudes of energy inputs. Literature was surveyed for each landform type and a particular location was chosen that had sufficient background data to use in energy calculations.

Table 3. List of landforms and their locations.

Landform Type	Special Sources	Location
Floodplain	Periodic river flooding	Huron River, SE Michigan
Coral reef	Shallow tropical blue water with waves	Florida Keys
Salt marsh	Tides and sediments	Sapelo Island, Georgia
Mountain glacier	Cold and humid with elevation gradient	Blue Glacier, Cascade Mountains, Washington
Palsa mound	Seasonal permafrost, freeze-thaw cycles	Devon Island, Canada
Desert sand dune	Dry winds and sediments	White Sands, New Mexico
Arroyo	Dry, pulsing rains, grazing pressure	Rio Puerco, NC New Mexico
Oyster reef	Pulsing salinity, tides	Crystal River, Florida
Marine mud mounds	Wind and current stirring sediments	Florida Bay, South Florida
Overburden spoil mounds	Strip mining	Polk County, Central Florida

CHAPTER 2
METHODS

Energy Analysis

Energy Circuit Language

The energy circuit language (Odum 1967, 1971, 1976, 1983; Odum and Odum 1981) was used to model land systems. This is a symbolic language for representing whole systems in diagrams. It has similarities with electrical circuit diagrams but has a richer content. The language is a kind of visual mathematics since each symbol configuration has a mathematical expression. Diagrams using the energy symbols have the same information as matrices and sets of equations but go beyond by containing the constraint of energy laws of conservation and entropy increase. Models of this type can be used for both kinetics and energetics. Use of the energy circuit language forces one to include important features, lessening the chance that something significant will be left out of the model. Artistic use of hierarchy is incorporated into the models by arranging the position of symbols. Units having low energy concentration (low quality) are drawn at the base of circuits while high energy units (high quality) are drawn at the end of circuits.

The general procedure in diagramming a system was to start by including the main energy sources then adding storage and pathways along which energy flows forward and back, finally leaving the system as dispersed heat or export to another system. Energy was used as a common denominator since all real flows and storages have energy value and because energy is the basis of causal action.

Expressing Energy in Equivalent Units

After diagramming, energy flows and storages were evaluated for their actual energy (heat) content. Equations for calculating actual energies are given below. Variables used in the equations are listed in appendix tables for each of the landforms analyzed. Much of these data were taken from a handbook of energy values for the United States (Odum et al. 1978).

1. Solar Insolation

   Values reported are surface measurements.

2. Wind Kinetic Energy

   $E = 0.5 \rho V^2 C(1/d)(2.38 \times 10^{-11}\ \mathrm{Cal/erg})(3.15 \times 10^7\ \mathrm{s/yr})$
   $(10^4\ \mathrm{cm^2/m^2})$;

   ρ = density of air = $1.2 \times 10^{-3}\ \mathrm{g/cm^3}$;

   V = wind velocity in cm/s;

   C = eddy diffusion coefficient = $10^4\ \mathrm{cm^2/s}$; and

   d = height of boundary layer = 10^4 cm.

3. Precipitation and Runoff Chemical Potential Energy

   $E = nRT \ln(C_2/C_1)M$;

   n = 1 mole/18 g H_2O;

   R = gas constant = (1.99 cal/°mole)(1 Cal/1000 cal)
   = 1.99×10^{-3} Cal/°mole;

   T = absolute temperature in °K;

   C_2 = water content of precipitation or runoff
   = 1,000,000 ppm − TDS of precipitation or runoff;

   C_1 = water content of receiving water

= 1,000,000 ppm - TDS of receiving water;

TDS = total dissolved solids in ppm; and

M = mass of precipitation or runoff per year in $g/m^2 \cdot yr$

= precipitation in cm/yr $(1\ g/cm^3)(10^4\ cm^2/m^2)$.

4. Precipitation Impact Kinetic Energy

$E = 0.5Mv^2(2.38 \times 10^{-11}$ Cal/erg);

M = mass of precipitation per year in $g/m^2 \cdot yr$

= precipitation in cm/yr $(1\ g/cm^3)(10^4\ cm^2/m^2)$; and

v = velocity of raindrops = 762 cm/s for an average drop diameter (Odum et al. 1978).

5. Runoff Elevated Potential Energy

$E = MGH_R(2.38 \times 10^{-11}$ Cal/erg);

M = mass of runoff per year in $g/m^2 \cdot yr$

= runoff in cm/yr $(1\ g/cm^3)(10^4\ cm^2/m^2)$;

G = gravitational acceleration = 980 cm/s^2; and

H_R = elevation drop or head in cm.

6. Tidal Potential Energy

$E = 0.5\rho GH_T^2n(2.38 \times 10^{-11}$ Cal/erg)$(10^4\ cm^2/m^2)$;

ρ = density of seawater = 1.025 g/cm^3;

G = gravitational acceleration = 980 cm/s^2;

H_T = tidal head in cm; and

n = number of tides per year.

7. Organic Inflow Potential Energy

$E = M_oc$;

M_o = mass of organic matter per year in $g/m^2 \cdot yr$;

c = heat content of organic matter = 4.5 Cal/g (E. P. Odum 1971).

8. Wave Potential Energy

$E = 1/8\rho G^{3/2}H_W^{5/2}W(2.38 \times 10^{-11}$ Cal/erg) $(3.15 \times 10^{7}$ s/yr);

ρ = density of seawater = 1.025 g/cm^3;

G = gravitational acceleration = 980 cm/s^2;

H_W = wave height in cm; and

W = width of area affected in m.

9. Flood Head Potential Energy

$E = \rho DGH_F F(1/A)(2.38 \times 10^{-11}$ Cal/erg);

ρ = density of water = 1 g/cm^3;

D = flood discharge in cm^3/s;

G = gravitational acceleration = 980 cm/s^2;

H_F = flood head or height in cm;

F = duration of flood per year in s/yr; and

A = area of flooded zone in m^2.

10. Uplift Potential Energy

$E = MGH_u$ $(2.38 \times 10^{-11}$ Cal/erg);

M = mass of uplifted material per year in g/m^2·yr

= height of uplift in cm/yr (, density of material)(10^4 cm^2/m^2);

G = gravitational acceleration = 980 cm/s^2; and

H_u = height of uplift per year in cm.

11. Storm Kinetic Energy

E = Sn;

S = kinetic energy per storm in Cal/m^2; and

n = number of storms per year.

12. Freeze-Thaw Cycle Energy

$E = H_{F-T}n$;

H_{F-T} = heat energy per freeze-thaw cycle

$= [(\Delta T)(H_c)(V_F) + (H_m)(V_F)](\Delta T/T)/\Delta t;$

ΔT = temperature change over freeze-thaw cycle in °C;

T = absolute temperature in °K;

H_c = heat capacity of soil substrate in $\mathrm{Cal/cm^3 \cdot {}^\circ C}$;

H_m = heat of melting = 8.0×10^{-2} $\mathrm{Cal/cm^3}$;

V_F = volume affected by freeze-thaw cycle in $\mathrm{cm^3/m^2}$;

Δt = length of cycle in days; and

n = number of daily cycles per year.

13. Sediment (sand or mixture) Potential Energy

$E = MGH$;

M = mass of accumulated sediments per year in $\mathrm{g/m^2 \cdot yr}$

$= \rho L(10^4\ \mathrm{cm^2/m^2})$;

ρ = density of sediments in $\mathrm{g/cm^3}$;

L = accumulation rate in cm/yr;

G = gravitational acceleration = 980 $\mathrm{cm/s^2}$; and

$H = 0.5L$.

14. Actual Potential Energy in Landforms

$E = MGH(2.38 \times 10^{-11}\ \mathrm{Cal/erg})(10^4\ \mathrm{cm^2/m^2})$;

M = mass of landform = ρV;

ρ = density of landform materials in $\mathrm{g/cm^3}$;

V = volume of a specified shape in $\mathrm{cm^3}$;

G = gravitational acceleration = 980 $\mathrm{cm/s^2}$; and

H = average height of landform in cm.

To convert energies to a common basis of equivalent work units or embodied energy, actual energy values were multiplied by energy transformation ratios (quality factors) that are ratios of Calories of solar energy per Calorie of another type.

Energy transformation ratios are energy transformation efficiencies defined as the amount of energy of the type required to develop unit energy of another type. Energy transformation ratios used in this study are given in Table 4, primarily from Odum and Odum (1980:7), who noted, "at this stage in energy analysis calculations are made objectively and documented with the realization that tables of conversion efficiencies will be improved with time." Other energy transformation ratios were calculated from case studies. Solar energy was used as the base quality unit in all calculations.

An overall ratio between energy and money was used to estimate energy embodied in high-quality goods and services. It was found by dividing the gross national product into the total energy use by the general economy, including purchased fuels and natural renewable energy, both in energy equivalents of the same quality. This ratio is the amount of energy used per unit dollar circulating in the economy, which takes into account the free natural energies contributing to the economy. For the United States in 1980, this ratio was 11,000 coal equivalent Calories per dollar (Odum and Odum 1980).

Parameters Used for Energy Analysis

From an elevated model, analysis was made of the magnitudes, distributions, and proportions of storages and flows of energies. All energies were translated into embodied energy equivalents of one type. Values and indices were calculated from the evaluated model to aid in assessment of sources, storages, and alternative actions as shown in Figure 5.

Table 4. Energy transformation ratios used to convert different energy sources into equivalent units of solar energy (from Odum and Odum 1980; Odum et al. 1978).

Energy Source	Transformation Ratios, Direct Solar Cal/Cal
Sun	1
Heat advection	12.6
Wind	74
Thunderstorms[a]	1100
Coal	2000
Organic inflows	2400
Waves	2700
Elevated potential of streams	3000
Petroleum and oil	3100
Tide, physical potential	3200
Chemical potential of rain over land	3600
Electricity	8000
Kinetic impact of rain	2.4×10^5
Flood currents	3.6×10^5
Geologic uplift	4.4×10^{12}

[a] Calculated in this study.

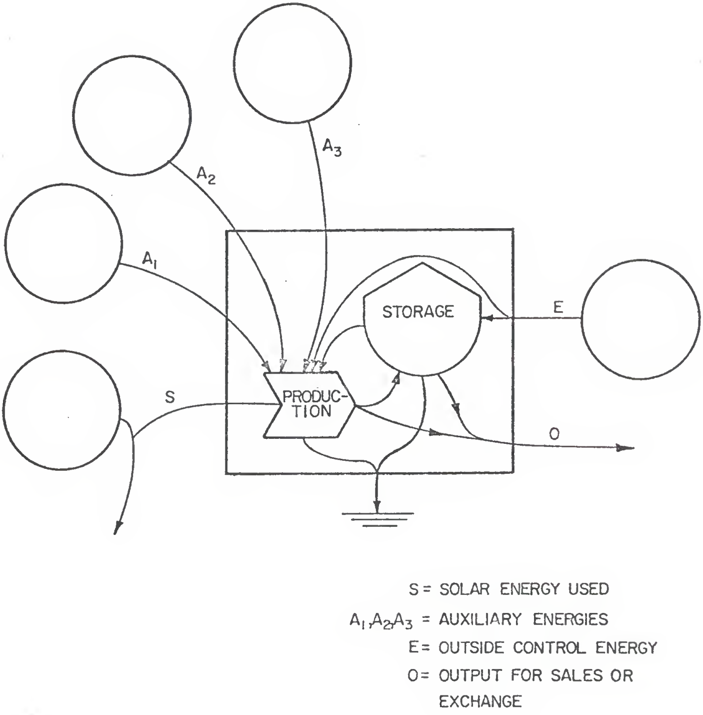

A3
A2
A1
S
STORAGE
E
PRODUC-TION
O
S = SOLAR ENERGY USED
A1,A2,A3 = AUXILIARY ENERGIES
E = OUTSIDE CONTROL ENERGY
O = OUTPUT FOR SALES OR EXCHANGE

Figure 5. Definitions used for energy analysis. Energy signature = S, A_1, A_2 . . . A_n, all in units of the same quality. Net energy of 0 = 0 - E, both in units of the same quality. Yield ration of 0 = 0/E. Total embodied energy flow, E_t = S + [(A_M - S) if positive] + A_n. Where A_M is energy of indirect solar origin and A_n is of non-solar origin (such as tide).

The energy signature is the set of all energy sources including solar, which is the principal natural external source, auxiliary energies such as wind, rain, and uplift—which are by-products of solar—and purchased energy such as goods, fuels, services, and capital investment from human economies.

The solar energy portion of the energy signature was calculated as the direct solar input plus the indirect (auxiliary) solar energy of the oceans and atmosphere driving weather and geological energies. The direct solar was first subtracted from each indirect energy to eliminate double counting and any positive remainder was added back to solar. This is the energy available to be used in landscape work. The sum of direct and corrected indirect energies was used to avoid counting auxiliary energy twice since they are by-products of direct sunlight.

Embodied energy in the long-term storage of landform was calculated by the equation given below

$$\text{Landform embodied energy} = E_T C D_T \tag{2.1}$$

where E_T = total embodied energy input in solar Cal/m$^2\cdot$yr; C = concentration area in m^2; and D_T = landform development time in years. Values for the total embodied energy input, E_T, are given in tables summarizing the energy signatures for each landform. Data on concentration area, C, and development time, D_T, are given in appendix tables for each landform.

Net energy of an output is the difference between the embodied energy of the output and the exchange energies used to extract the output. The yield ratio of this extraction process is the output energy divided by the exchange energies.

Successional Model

A model of succession was simulated to test alternatives for accelerating ecological development. Modeling was done using the mathematical expressions that accompany the energy circuit language. Figure 6 shows the model along with the expressions for storages and pathways. Three stages of succession are shown with storages corresponding with biomass: Q_3 is grasses, Q_2 is pines, and Q_1 is hardwoods. Q_4 is litter storage that receives input from all stages of succession.

The main driving energy source was sunlight, which is apportioned according to the maximum stature and efficiency of each successional stage. Hardwoods capture the most sunlight since they grow to be the tallest and are the most efficient with only the sunlight remaining being available to pines and grasses. Pines get the next use of sunlight followed by the grasses, which get the remainder from the pines. This was a way of simulating shading effects that incorporate kinetics of limiting availability of sunlight.

Initially storages were started at zero and each received germination inputs from outside seed sources. Seeding input to pines and hardwoods were controlled by threshold switches of the litter storage. These switching controls on germination were related to changing microclimates of the forest floor, which allow germination of seeds. An additional threshold of light level was also incorporated as control on hardwood germination. The model was run with and without this switch for comparison when light was potentially limiting to germination.

The model was calibrated with data largely from Georgia old field studies. Timing of stages was adjusted through germination thresholds to Florida phosphate succession, which is much faster than Georgia old field succession. The model was simulated with a 1-quarter-year (3 month) time

$\dot{Q}_1 = K_2Q_1R_1 - K_3Q_1 - K_4Q_1$ ($+S_1$ IF $R_2 < T_3$ and $Q_4 > T_1$)

$\dot{Q}_2 = L_2Q_2R_2 - L_3Q_2 - L_4Q_2$ ($+S_2$ IF $Q_4 > T_2$)

$\dot{Q}_3 = M_2Q_3R_3 - M_3Q_3 - M_4Q_3 + S_3$

$\dot{Q}_4 = K_4Q_1 + L_4Q_2 + M_4Q_3 - N_1Q_4$

$R_1 = J/(1 + K_1Q_1)$

$R_2 = R_1/(1 + L_1Q_2)$

$R_3 = R_2/(1 + M_1Q_3)$

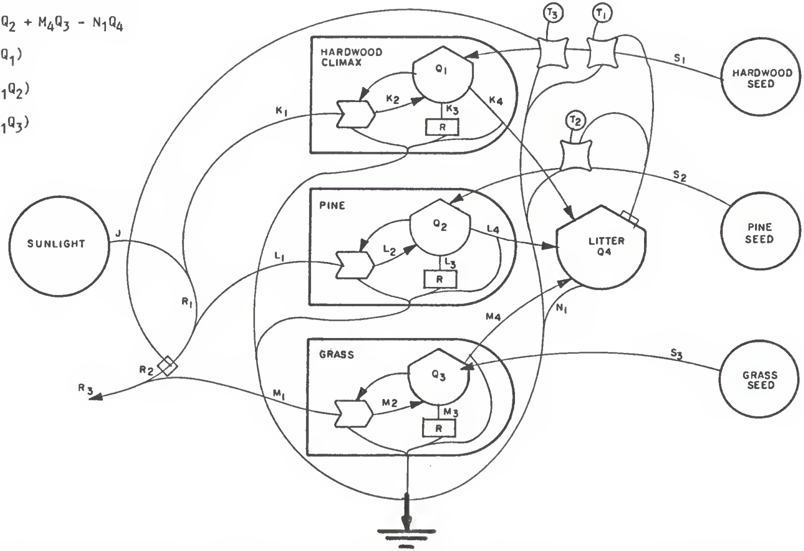


Figure 6. Simulation model of succession in southeastern United States. State variables Q_1, Q_2, and Q_3 are biomass in successional stages. Q_4 is the mass of litter developed by the successional systems.

interval. Smaller time steps were used in runs simulating litter data for validation. Simulations were run on an Intecolor 8000 desk-top computer using BASIC.

Ecological Field Measurements

Ecosystem Parameters

Percent vegetation cover was estimated visually from 0.25-m^2 plots. Cover measurements were taken every 3 meters over transects ranging in length from 6 to 36 meters depending on the particular conditions of the surface. Sample sizes were 60 plots on 1-year-old mounds, 92 plots on 5-year-old mounds, 68 plots on 10-year-old mounds, and 84 plots on 20-year-old mounds. On the oldest sites cover was estimated from aerial photographs. Optical density as an index of biomass (Odum et al. 1963a) was measured with a portable solar radiometer (Matrix Inc., Mark IV solarimeter), which reads percent transmittance between a setting made in a clearing and that under canopy. Sample sizes were 73 on 1-year-old mounds, 73 on 5-year-old mounds, 59 on 10-year-old mounds, 80 on 20-year-old mounds, 84 on 50-year-old mounds, and 60 at San Felasco. Percent transmittance was converted to optical density by dividing by the cosine of the angle between the position of the sun and the vertical position, then taking the log and changing sign. Because of the trigonometric transformation no estimates of embodied energy were calculated. Measurements were taken under vegetation at ground level. Tree height was measured for canopy-level trees with a Haga altimeter. Sample sizes were 16 trees on 10- and 20-year-old mounds and 20 trees on 50-year-old mounds and at San Felasco. Ten litter samples were taken by hand from 0.25-m^2 plots at each age mound. Samples were dried at 60°C for 24 hours and weighed. Litter depths were measured whenever litter was greater than 0.3 cm deep. At lesser depth, litter was too sparse to form a distinct layer.

Sample sizes were 32 on 5-year-old mounds, 20 on 10-yearold mounds, 32 on 20-year-old mounds, 60 on 50-year-old mounds, and 64 at San Felasco.

Soil organic matter was measured by loss on ignition. Ten soil samples were taken from the upper 10 cm for each age mound. Subsamples of these were dried at 60°C for 24 hours and weighed, then ashed at 500°C for 1 hour and weighed again. Organic matter was estimated as the difference between the dry weight and ashed weight. Organic matter values obtained with this technique may be overestimated because of combustion of water bound to clays that is lost in addition to combustion of organic matter.

Soil profiles were also described from the youngest (1 year old) and from one of the oldest (50 year old) sites. Descriptions were based on two one-meter-deep and two half-meter-deep soil pits at each site. Ant nests as an index of soil animal activity were counted in 0.25-m^2 plots used for vegetation cover determination. No estimates of standard error were calculated since so few plots had nests. Data are reported as nests per 10 m^2. Sample sizes were 60 plots (15 m^2) on 1-year-old mounds, 92 plots (23 m^2) on 5-year-old mounds, and 87 plots (21.75 m^2) on 10-year-old mounds. Because of the density of vegetation it was not possible to count nests at sites older than 10 years.

Trees greater than 10 centimeters dbh were sampled for density, and basal area was calculated at the 50-year-old sites and at San Felasco. Three 900-m^2 plots at the site in the Payne Creek mine and at San Felasco and five 450-m^2 plots at Christina were sampled. The smaller plot size at Christina was due to the shorter length of the slopes (about 15 meters at Christina and about 30 meters or more at the Payne Creek mine and at San Felasco). Importance values were used to assess the biological contribution of a tree species to the forest community. Importance was defined as the sum of relative density plus relative dominance (as measured by basal area in m^2/ha) divided by two to put the index on a percentage basis. This definition omits frequency that was originally included by Curtis and McIntosh (1951). Because of the small number of plots and their large size, frequency values were high and would inflate importance percentages (see also Daubenmire 1968). A measure of relative frequency in terms of percent occurrence in the total number of plots, however, was included separately.

Indices for Comparison of Forests

One of the goals of the field studies was to determine the extent to which succession has restored the natural ecosystems on spoil mounds. One way this was accomplished was by comparing indices of tree community structure of the oldest phosphate forests with a "climax analog," San Felasco Hammock, near Gainesville. Five indices were used—the Holdridge Complexity Index (Holdridge 1967), species per 1000 individuals (Odum, Cantlon, and Kornicker 1960; Margalef 1958), the Shannon Index (Shannon and Weaver 1963; Margalef 1958), and the Simpson Index (Simpson 1949) along with a floristic similarity index (Sorensen 1948).

The Holdridge complexity index is calculated as follows:

$$CI = \frac{HBDS}{1000} \tag{2.2}$$

where H = average height of the three tallest trees (m); B = basal area (m^2/ha); D = density (number of stems of 10 centimeters dbh or greater/ha); and S = number of species (of 10 centimeters dbh or greater). These values are usually extrapolated from a 0.1-hectare sample area, but in this study data were based on the total sample areas of 0.5 hectares at the phosphate forest and 0.27 hectares at San Felasco.

Cumulative species per 1000 individuals is an expression of the approximate logarithmic distribution of commonness and rarity in natural communities. The index is usually found by plotting the cumulative appearance of new species as a function of the logarithm of the cumulative number of individuals examined. Here species per 1000 was found by back extrapolating from a straight line plot passing through the origin and the point established by the log of the total individuals counted versus the number of species found.

The Shannon Index, derived for the theory of communication, has often been used as a measure of diversity in ecological communities. Its expression is

$$H = -\sum (P_i) \log_2 (P_i) \tag{2.3}$$

where $P_i = (n_i)/N$ = observed frequency for each species; n_i = number of individuals for each species; and N = total of all individuals. The units of this index calculated with $\log_2$ are in "bits per individual."

Simpson's Index is defined as

$$C = 1 - \sum (n_i/N)^2 \tag{2.4}$$

with n_i and N as above. This index ranges from a minimum diversity of zero with one individual of one species toward a maximum diversity of one when n_i is small and N is large.

Similarity between floristic species composition was measured with the Sorensen Index given below

$$S = [2w/(a + b)] \times 100 \tag{2.5}$$

where a = number of species in community a; b = number of species in community b; and w = number of common species between communities a and b. This index has the form of a percentage ranging from a minimum of zero when there are no common species (w = 0) to 100 when all species are held in common (w = a = b).

CHAPTER 3
RESULTS

Embodied Energy of Natural Landforms

For each type of landform developed in geological, ecological, and cultural work, a model is given showing the main driving energies, system processes, and storages. The energy signature is shown with a table of embodied energy flows. Then data are given for representative storage parameters and development times involved. The role of these data tables was to document the range of variability of landform dimensions and process rates in reference to the site chosen for case study. Finally results of calculations estimating magnitudes of embodied energy in resulting landforms are given.

Embodied Energy in Floodplain

A floodplain is a landform organized by river flooding. Many floodplains are composed of sediments deposited by river floods. These have much organic sediment from floodplain vegetation. Vegetation of floodplains is usually better developed than its surroundings due to rich soils and a longer hydroperiod. A model of a floodplain is shown in Figure 7. The flood is shown as a switch operated by a comparison of water volume and channel volume. When water volume is greater than channel volume, flooding occurs leading to deposition of sediments, which make up the floodplain landform. Table 5 provides background data on floodplains.

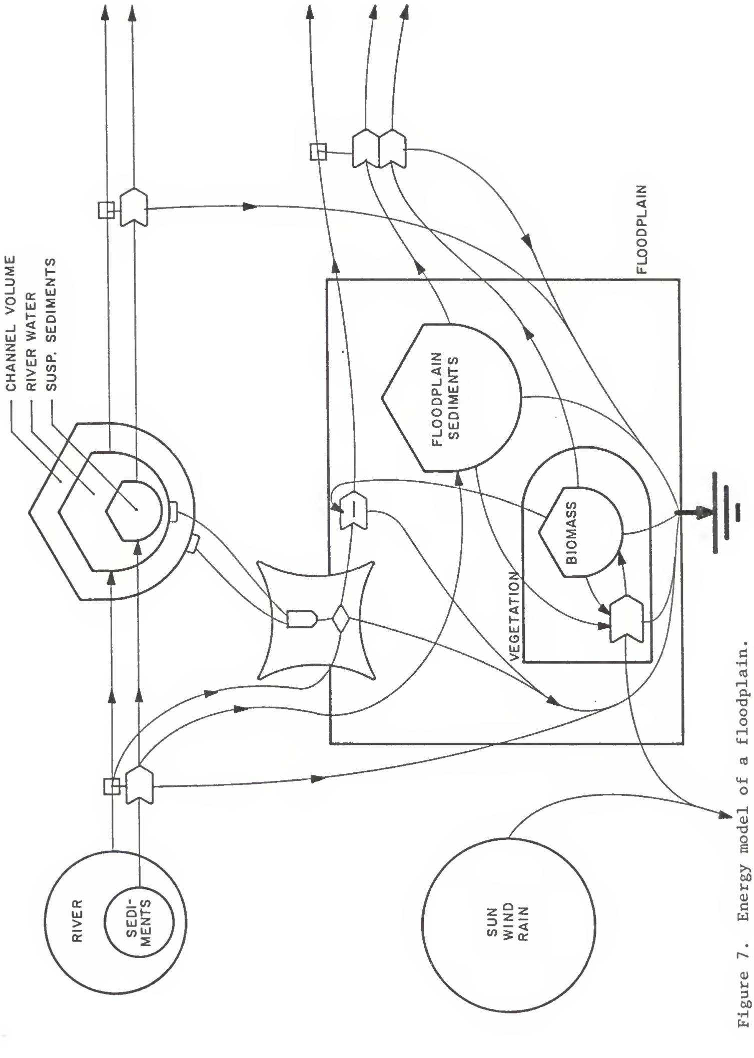


Figure 7. Energy model of a floodplain.

Table 5. Floodplain characteristics.

Location	Storm Runoff, Inches	Storm Duration, Hours	Thickness of Deposit, Feet	Floodplain Area, Feet^2	Basin Area, Miles^2	Reference
Klamath Mts., CA	10.7	72	1.3	4.6×10^6	---	Stewart and Lamarche 1967
Bijou Creek, CO	12	1	2–3	2.4×10^8	1444	McKee et al. 1967
Quinebaug River, CT	18	96	0.02–3	7.7×10^3	157	Wolman and Eiler 1958
Huron River, MI	3.3	24	---	1.1×10^9	900	Say and Jansson 1976; Corps of Engineers 1976

Average deposition is about 1 foot per major flood. For case study the Huron River in southeastern Michigan was chosen. The energy signature of the Huron River floodplain is given in Table 6. The dominant energies are organic materials deposited by floods and the physical energy in the flood itself. Using a development time of 10,000 years (time since glacier recession) gives the embodied energy of 1.0 x 10^{12} solar Cal/m^2.

Embodied Energy in Coral Reef

Coral reefs are found throughout shallow tropical water that is low in nutrients. The system is mostly nonliving calcium carbonate skeletons of corals and algae with a covering of living biomass. A coral reef model is shown in Figure 8. The main storage is reef form, which interacts with waves and tides to form turbulence. Because of the concentrated biomass, turbulence allows the exchange of oxygen, disposal of wastes, and acquisition of food and nutrients from the surrounding waters. Calcium input is shown but was not evaluated. Background data on reef growth and current velocity for several reefs are given in Table 7. An energy signature for the Florida Key reefs is given in Table 8 and was used as a case study. For a 7-meter section, as in the Pleistocene Florida Key reef, embodied energy was found to be 5.1 x 10^{16} solar Cal/m^2.

Embodied Energy in Salt Marsh

Along low gradient sedimentary coasts, marshes develop with salt-adapted grasses. In certain areas of resistant rock, marshes can develop on their own peat with little inorganic sediment. A salt marsh model is shown in Figure 9. Turbulence in marsh waters from tide causes transport of inorganic sediments and organic matter out of marsh. Vegetation decreases turbulence by friction and leads to deposition of sediment that

Table 6. Floodplain case study energy signature (data on actual energy flows are given in Appendix II-A).

Energy Source	Actual Energy Flow, Cal/$m^2 \cdot$yr	Energy Transformation Ratio, solar Cal/Cal	Embodied Energy Flow, 10^6 solar Cal/$m^2 \cdot$yr
Sun	1,000,000	1	1.0
Wind	1,000	74	0.07
Chemical potential of rain	2.4	3,600	0.08
Elevated potential of runoff	0.6	3,000	0.002
Kinetic impact of rain	5.4	240,000	1.3
Organic inflows	1,500	2,400	3.6
Flood head	4.7	360,000	1.7
Total embodied flow			4.6

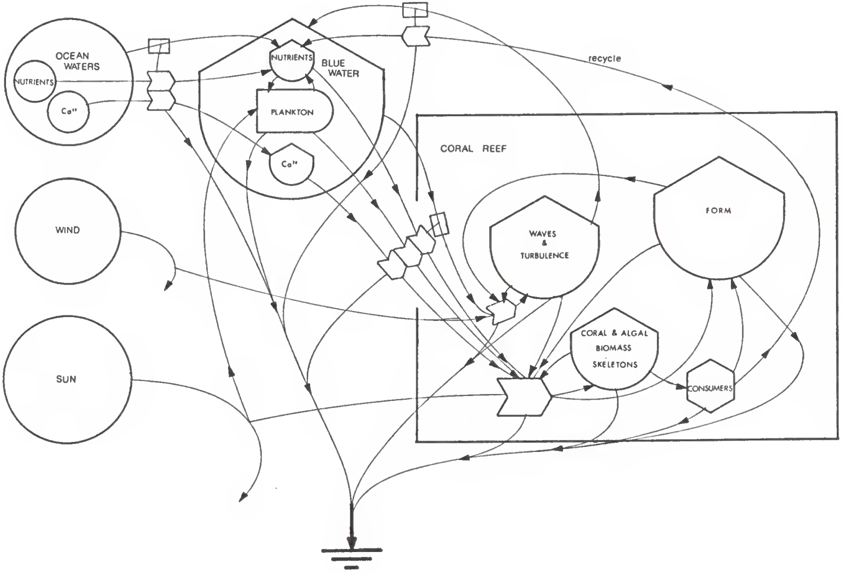


Figure 8. Energy model of a coral reef.

Table 7. Coral reef characteristics.

Location	Reef Growth, cm/yr	Current Velocity, cm/s	Reference
Range for Caribbean Reefs	0.9–1.5	---	Adey 1978
Eniwetok	1.6[a]	0.49	Odum and Odum 1955
Pleistocene Reef, Florida Keys	0.43–0.85	---	Hoffmeister and Multer 1964
Grand Cayman Islands	---	0.35	Roberts et al. 1976

[a] More recent evidence suggests that no net reef growth may have occurred over the last few thousand years (Smith 1973).

Table 8. Coral reef case study energy signature (data on actual energy flows are given in Appendix II-B).

Energy Source	Actual Energy Flow, Cal/$m^2 \cdot yr$	Energy Transformation Ratio, solar Cal/Cal	Embodied Energy Flow, 10^6 solar Cal/$m^2 \cdot yr$
Sun	1,500,000	1	1.5
Wind	650	74	0.05
Zooplankton	3,300	2,400	7.9
Tide	140	3,200	0.4
Waves	46,000,000	2,700	124,200.0
Total embodied flow			124,206.8

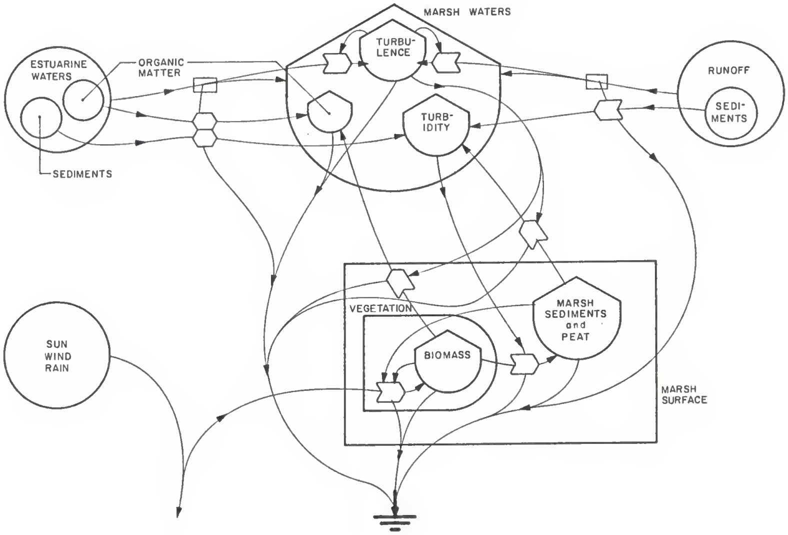


Figure 9. Energy model of a salt marsh.

comprise the form of the marsh. Table 9 gives background data on salt marshes. Accumulation rates range from 0.2 cm/yr to 20 cm/yr, indicating a range of energy conditions. Using Sapelo Island, Georgia, as a case study, an energy signature of a marsh is given in Table 10. Tidal energies are highest, providing flushing actions and building intricate channel networks. Assuming a development time of 300 years, the embodied energy of the salt marsh is 9.7×10^9 solar Cal/m^2.

Embodied Energy in Mountain Glacier

Glaciers are massive storages of ice found in polar and alpine regions. A model of a mountain glacier is shown in Figure 10. Main storages of the glacier are snow and ice. The transformation of snow to ice is shown as a function of pressure. The important role of glacier ice in erosion is shown as a drain on mountain storage. However, some of this energy cycles back to amplify uplift and mountain building. Background data on glaciers are given in Table 11. Blue Glacier in the Cascade Mountains of Washington State was chosen as a case study. A general energy signature for the Cascades is given in Table 12. Uplift is the largest energy source. Using a development time of 30,000 years, the embodied energy of the Blue Glacier was calculated at 2.6×10^{14} solar Cal/m^2.

Embodied Energy in Palsa

Palsa are ice-cored mounds found in northern bogs with discontinuous permafrost. They have a thick cover of moss and peat, which insulates and maintains the mound. Ice is concentrated from the surrounding bog waters and its expansion causes the mound to be elevated. Figure 11 shows a model of a palsa. Vegetation and peat are shown as a drag on heat inputs and outputs from the mound. Flows between water and ice in the mound are

Table 9. Salt marsh characteristics.

Location	Dominant Sediment Type	Accumulation Rate, cm/yr	Development Time, years	Reference
Barnstable, MA	Peat	---	4000	Redfield 1972
Poole Harbour, England	Silt	10–20	---	Chapman 1976
Scolt Head Island, England	Silt	0.20–0.84	---	Chapman 1976
Temperate Marshes, European and North-Eastern America	----	0.20–1	10–330[a]	Ranwell 1972
Norfolk, England	Silt	---	500	Steers 1977
Sapelo Island, GA	Silt	0.4	---	Letzsch and Frey 1980

[a] Minimum age to maturity.

Table 10. Salt marsh case study energy signature (data on actual energy flows are given in Appendix II-C).

Energy Source	Actual Energy Flow, Cal/$m^2 \cdot yr$	Energy Transformation Ratio, solar Cal/Cal	Embodied Energy Flow, 10^6 solar Cal/$m^2 \cdot yr$
Sun	1,300,000	1	1.3
Wind	630	74	0.05
Chemical potential of rain	1,100	3,600	3.9
Elevated potential of runoff	0.5	3,000	0.001
Kinetic impact of rain	8.2	240,000	2.0
Tide	4,000	3,200	12.8
Total embodied flow			17.4

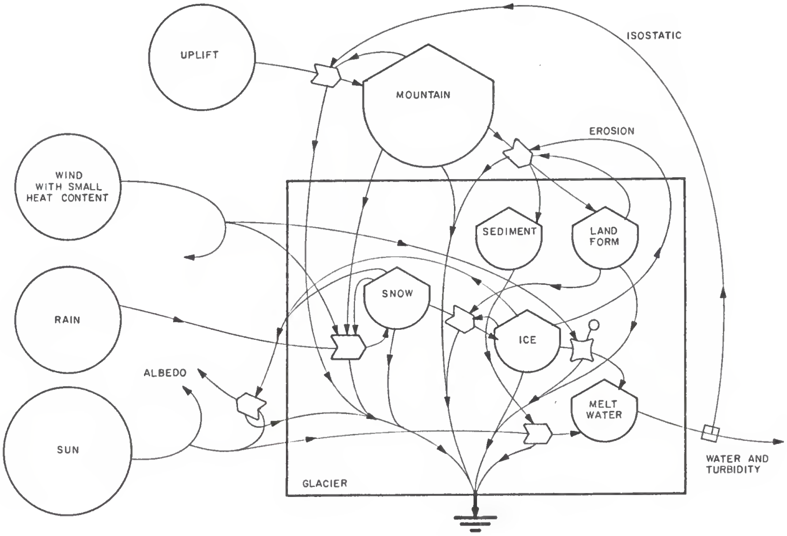


Figure 10. Energy model of a mountain glacier.

Table 11. Glacier characteristics.

Glacier	Location	Density, g/cm^3	Depth, m	Area, km^2	Volume, km^3	Elevation	Net Growth,[a] m^3/yr
Blue Glacier[b]	Washington	0.88	---	4.3	0.57	1275—2350	2.2×10^6
Lemon Creek[c]	Juneau Ice Field	0.55	150	9.21	1.38[d]	500—1500	1.3×10^7
Seward-Malaspina[e]	Canada-Alaska Border	----	---	4274	1751	2134	1.5×10^9
Boas[f]	Gaffin Island, N.W.T.	0.328[g] 0.8[h]	---	1.45	0.001[d]	850—1350	5.8×10^5

[a] Usually given as water volume.
[b] Lachapelle 1965.
[c] Marcus 1964.
[d] Calculated from dimensions given in reference.
[e] Sharp 1951.
[f] Andrews 1975.
[g] Snow.
[h] Ice.

Table 12. Glacier case study energy signature (data on actual energy flows are given in Appendix II-D).

Energy Source	Actual Energy Flow, Cal/m^2·yr	Energy Transformation Ratio, solar Cal/Cal	Embodied Energy Flow, 10^6 solar Cal/m^2·yr
Sun	600,000	1	0.6
Wind	1,300	74	0.09
Chemical potential of rain	6.1	3,600	0.02
Uplift	5.8×10^{-5}	4.4×10^{12}	255.2
Total embodied flow			255.2

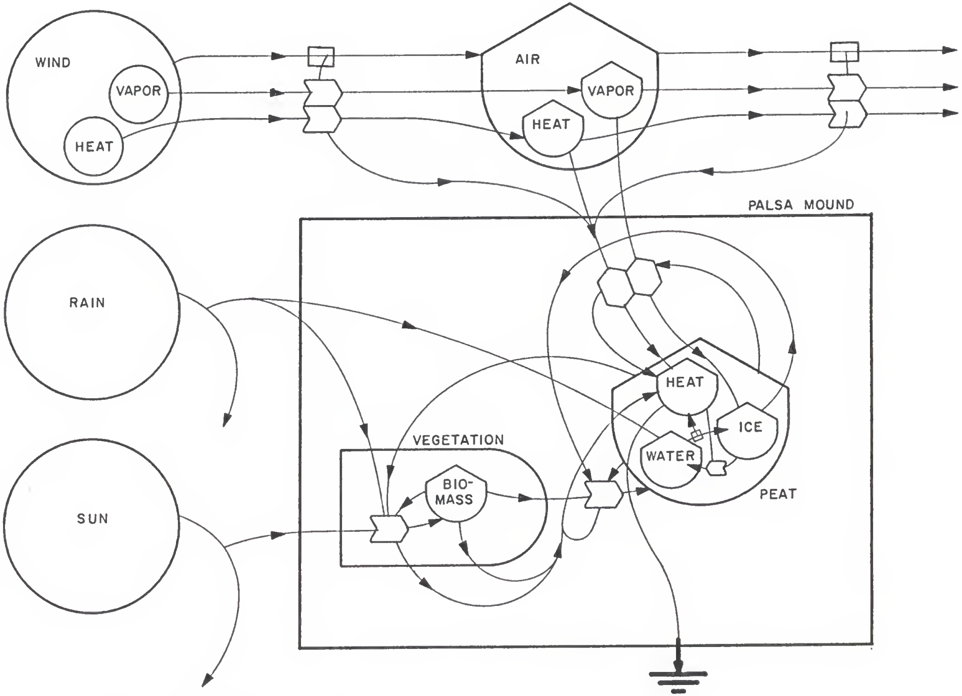


Figure 11. Energy model of a palsa mound with ice core.

shown as controlled by heat storage. Ice grows with heat loss to the atmosphere. Table 13 provides background data on palsa height and age. Much controversy exists concerning the formation of palsa as indicated by the wide range in ages. For case study, data for Devon Island were used. An energy signature of Devon Island is given in Table 14. As has been pointed out for these types of systems (Sigafoos 1952), the dominant energy is in the freezing and thawing of soils and waters, which lead to the concentration of ice in the mound form. Embodied energy in the Devon Island palsa is 9.2×10^9 solar Cal/m^2.

Embodied Energy in Sand Dune

In deserts and along coasts with ample sand supply and little vegetation, sand accumulates in sculptured mounds or dunes. Some dunes are fixed, while others move by cumulative saltation across landscapes. A model of a sand dune is given in Figure 12. Sand, carried by wind, is deposited to form the dune by the action of vegetation slowing wind velocity. Background data are given in Table 15. Accretion rates range from 3 to 200 cm/yr. Using White Sands, New Mexico, as a case study, an energy signature was calculated (Table 16). Although dunes are often thought to be built by wind energy, sand is found to be the largest embodied energy input. Embodied energy of the White Sands National Monument dunes was found to be 3.0×10^{10} solar Cal/m^2.

Embodied Energy in Arroyo

In the southwestern regions of the United States and to some extent in other arid regions, sharply cut drainage channels called arroyos develop. Their origin has been related to sparse vegetation and desert rain regimes; though there exists some controversy as to the actual cause.

Table 13. Palsa mound characteristics.

Location	Palsa Height	Age, yr	Reference
Yukon-N.W. Territory Canada	4 m	1220	Kershaw and Gill 1979
Devon Island, Canada	2–3 m	2400–7000	Brown 1973
Northwest Finland	3 m	7800–8000	Salmi 1970
Fennoscandia (regional averages)	up to 7 m	3000–3500	Ruuhijarvi 1970
Northern Ontario, Canada	---	200	Railton and Spalding 1973

Table 14. Palsa case study energy signature (data on actual energy flows are given in Appendix II-E).

Energy Source	Actual Energy Flow, $Cal/m^2 \cdot yr$	Energy Transformation Ratio, solar Cal/Cal	Embodied Energy Flow, 10^6 solar $Cal/m^2 \cdot yr$
Sun	200,000	1	0.2
Wind	200	74	0.01
Chemical potential of rain	0.8	3,600	0.003
Elevated potential of runoff	0.5	3,000	0.001
Heat flux in freeze-thaw cycle	180,000	12.6	2.3
Total embodied flow			2.3

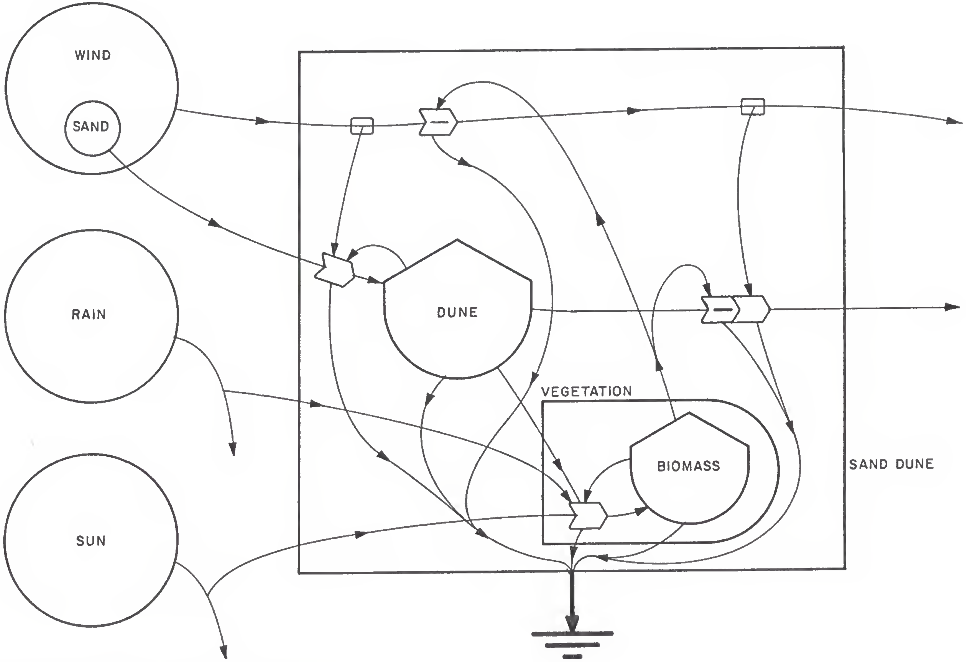


Figure 12. Energy model of a sand dune.

Table 15. Sand dune characteristics.

Location	Height, cm	Accretion Rate, cm/yr	Development Time, yr	Average Wind Speed, m/s	Reference
White Sands National Monument	549	60	(9)[a]	6.7	McKee and Douglas 1971
Braunton Burrows	250	(31)	8	---	Willis et al. 1959
Camel Estuary	400	(20)	20	---	Hepburn 1944
Newborough Warren	1520	70	50	---[b]	Ranwell 1958, 1972
Lake Michigan	---	30	--	---	Olson 1958
Island Beach State Park	610	20	--	---	Martin 1959
Lake Michigan	6000	200	--	---	Cowles 1899
Salton Sea Area	915	(3)	300	---	Long and Sharp 1964
	198	(25)	8	---	Long and Sharp 1964

[a] Values in parentheses have been calculated from data given in the original references. Development time was found by dividing rate of accretion into height of dune. Rate of accretion was found by dividing height of dune by development time.

[b] According to Ranwell (1958) most sand was moved during gales (wind speed $\geq$ 15 m/s), which occurred on 21 days/yr.

Table 16. Sand dune case study energy signature (data on actual energy flows are given in Appendix II-F).

Energy Source	Actual Energy Flow, Cal/m^2·yr	Energy Transformation Ratio, solar Cal/Cal	Embodied Energy Flow, 10^6 solar Cal/m^2·yr
Sun	1,200,000	1	1.2
Wind	2,000	74	0.1
Chemical potential of rain	0.6	3,600	0.002
Elevated potential of runoff	0.2	3,000	0.0006
Kinetic impact of rain	1.4	240,000	0.3
Sand	---	---	330[a]
Total embodied flow			330

[a] Embodied energy of sand: to calculate embodied energy in sand, data from a weathering experiment were used (Millot 1970). The experiment consisted of placing fresh crushed granite rock (800 kg) in a lysimeter and exposing it to natural energies for 30 years. The mass of sand sediment weathered in the experiment was 7.1×10^5 g. Assume a sunlight value of 1×10^6 solar Cal/m^2·yr and a lysimeter of 10 m^2. Embodied energy in sand is

$$\frac{(1 \times 10^6 \text{ solar Cal/m}^2\cdot\text{yr})(30 \text{ years})(10 \text{ m}^2)}{7.1 \times 10^6 \text{ g sand}} = 400 \text{ solar Cal/g.}$$

Using an accretion rate of 60 cm/yr and a density of 1.4 g/cm^3 the embodied energy in sand flow is (60 cm/yr)(10^4 cm^2/m^2)(1.4 g/cm^3)(400 solar Cal/g) = 330×10^6 solar Cal/m^2·year.

This region has high grazing intensities that alter natural vegetation that may have controlled erosion in the past. A model of an arroyo is given in Figure 13. The main storage is channel volume, which drains the watershed of the small amounts of rain characteristic of these areas. Biomass is small and appears to exert little control. Background data are given in Table 17. The extremely fast erosion rates are notable, especially considering volumes of the channels. An energy signature was calculated (Table 18) for the area of Rio Puerco, New Mexico, as case study. The highest energy is from storm rains. Embodied energy of the arroyo was calculated at 5.1×10^9 solar Cal/m^2.

Embodied Energy in Oyster Reef

Oyster reefs are dense accumulations of oyster shell formed in turbid coastal river mouths and intertidal zones. Unlike coral reefs, these are consumer reefs of low diversity. They are adapted to somewhat narrow salinity ranges of about 25‰ to 15‰. An oyster reef model is shown in Figure 14. The storage of shell interacts with tide forming currents and turbulence. Currents are used to bring in food and remove wastes, as with the coral reef. Oysters filter plankton and detritus from surrounding water and return nutrients by way of recycle. Background data for several reef parameters are given in Table 19. Crystal River, Florida, was used as a case study with some data from other locations. An energy signature for Crystal River is given in Table 20. Highest energy is in the plankton organic matter followed by chemical potential in runoff. The latter is significant in that it represents the energy necessary to control the salinity range in which oysters are found. Using the Mobile Bay

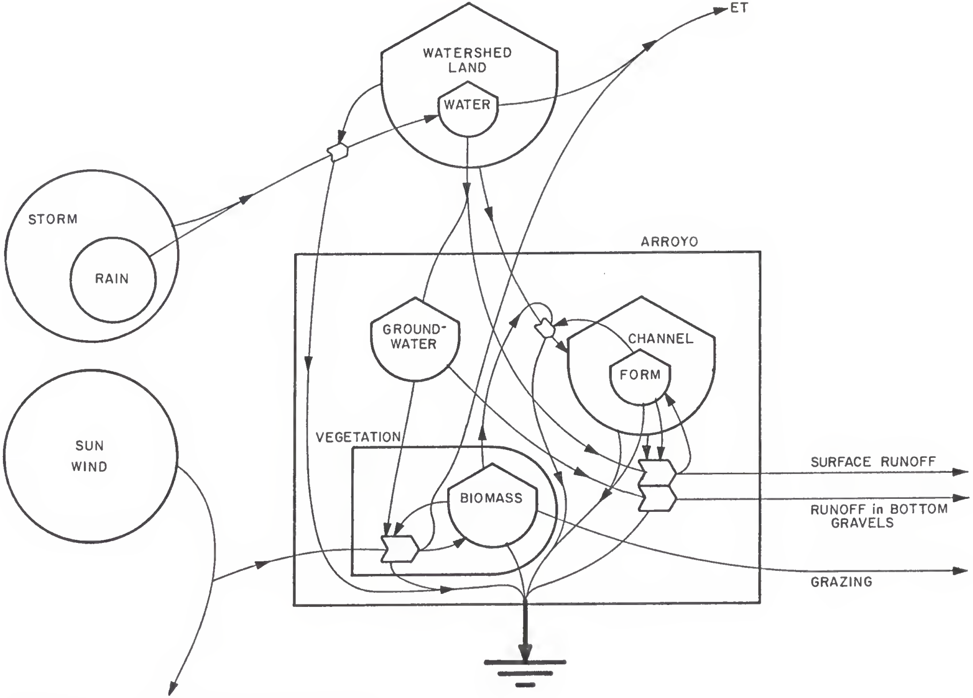


Figure 13. Energy model of an arroyo.

Table 17. Arroyo characteristics.

Location	Length, miles	Width, ft	Depth, ft	Volume, ft^3	Erosion Time, yr	References
Rio Puerco, New Mexico	150	285	28	6.3×10^9	43	Leopold et al. 1964
Rio Grande at Las Cruces, New Mexico	1400	18,480	25	3.4×10^{12}	2620	Ruhe 1962
Tesuque Valley, New Mexico	13	100	8–10	6.2×10^7	77	Miller and Wendorf 1958
Whitewater Arroyo, Arizona	20	100	13	1.4×10^8	25	Antevs 1952

Table 18. Arroyo case study energy signature (data on actual energy flows are given in Appendix II-G).

Energy Source	Actual Energy Flow, $Cal/m^2 \cdot yr$	Energy Transformation Ratio, solar Cal/Cal	Embodied Energy Flow, 10^6 solar $Cal/m^2 \cdot yr$
Sun	1,200,000	1	1.2
Wind	710	74	0.05
Chemical potential of rain	0.7	3,600	0.002
Kinetic impact of rain	1.4	240,000	0.3
Storm	30,000	1,100[a]	33.0
Total embodied flow			33.0

[a] Storm energy transformation ratio: Assume an average thunderstorm diameter of 5 km (Blair and Fite 1965) and a 10:1 concentration area over which the storm draws its energy. The area of the storm is

$$A = r^2 = (3.1416)(2500\ m)^2(10\ m^2/m^2) = 2 \times 10^8\ m^2.$$

Bennett and Chorley (1978) give the life span of a storm at about 1 hour with a kinetic energy of about 10^{11} joules or 2.5×10^7 Cal. Using the sunlight values from above, the embodied energy of the storm is

$$(1.2 \times 10^6 \text{ solar } Cal/m^2 \cdot yr)(2 \times 10^8\ m^2)(1\ hr/storm)/(8760\ hr/yr)$$

$$= 2.7 \times 10^{10} \text{ solar Cal.}$$

The storm energy transformation ratio is then

$$(2.7 \times 10^{10} \text{ solar Cal})/(2.5 \times 10^7 \text{ Cal}) = 1.1 \times 10^3 \text{ solar Cal/Cal.}$$

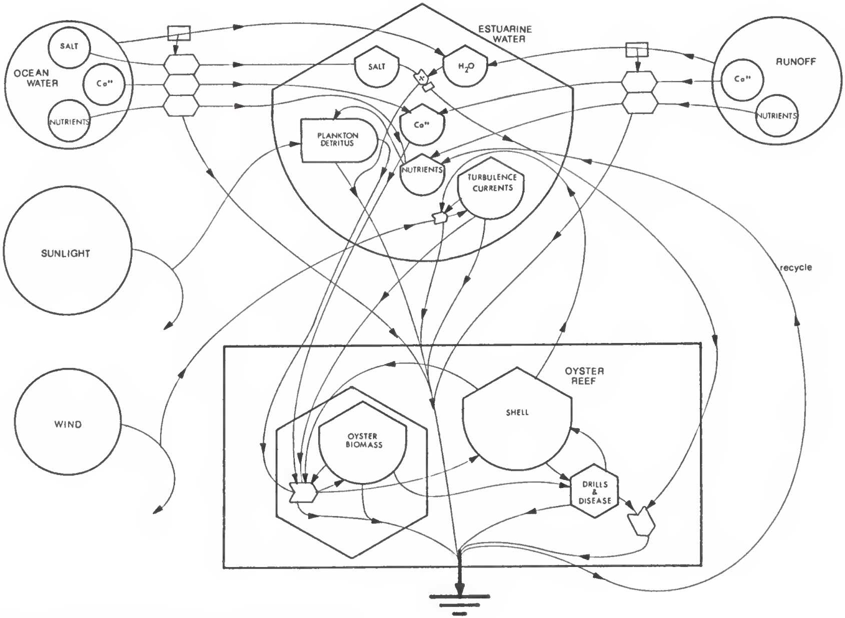


Figure 14. Energy model of an oyster reef.

Table 19. Oyster reef characteristics.

Location	Biomass, g/m^2	Age, yr	Thickness, ft	Reference
Intertidal Crystal River	269.1	--	--	Lehman 1974
Mobile Bay	--	920	8	May 1971
	190–234	--	--	Bernard 1974
Texas	--	--	20	Norris 1953
Intertidal North Inlet	310–500	--	--	Dame 1976
Intertidal Sapelo Island	1108	--	--	Bahr 1976

Table 20. Oyster reef case study energy signature (data on actual energy flows are given in Appendix II-H).

Energy Source	Actual Energy Flow, Cal/m^2·yr	Energy Transformation Ratio, solar Cal/Cal	Embodied Energy Flow, 10^6 solar Cal/m^2·yr
Sun	1,500,000	1	1.5
Wind	840	74	0.06
Chemical potential of runoff	48,000	3,600	172.0
Tide	410	3,200	1.3
Organic inflows	110,000	2,400	264.0
Total embodied flow			435.8

reef development time, the embodied energy was found to be 1.1 x 10^{13} solar Cal/m^2.

Embodied Energy in Florida Bay Mud Mounds

In the shallow waters of Florida Bay off the southern tip of peninsular Florida is found a unique type of carbonate mud mound. The mud is largely produced by carbonate-depositing algae, and the mounds are bound with the roots of seagrasses on which the algae grow. A model of the Florida Bay mounds is shown in Figure 15. Turbulence from wind, tide, and currents tends to suspend the calcareous mud in the water column. However, the seagrass acts to decrease turbulence by friction, which causes turbidity to settle. Calcium carbonate particles and mound form are built directly by algal biomass. Data were taken from Scholl (1966) and Enos and Perkins (1979). An energy signature for Florida Bay is given in Table 21. The highest energy is from chemical runoff from drainage of the Everglades, which regulates water chemistry in the bay. Based on radiocarbon dating of mounds, embodied energy in mud mounds was found to be 7.5 x 10^{10} solar Cal/m^2.

Energy and Phosphate Landscape of Central Florida

Whereas the energy systems developing landforms in the section previously considered were largely without humans, the world's landscapes are increasingly dominated by human management with huge energies from fuels, nuclear energy, etc. reforming land. The study results of human-nature interactions in landforms affected by phosphate strip mining are given in this section. Data on the work of nature in succession on old mined land are also given and compared with human effort of reclamation.

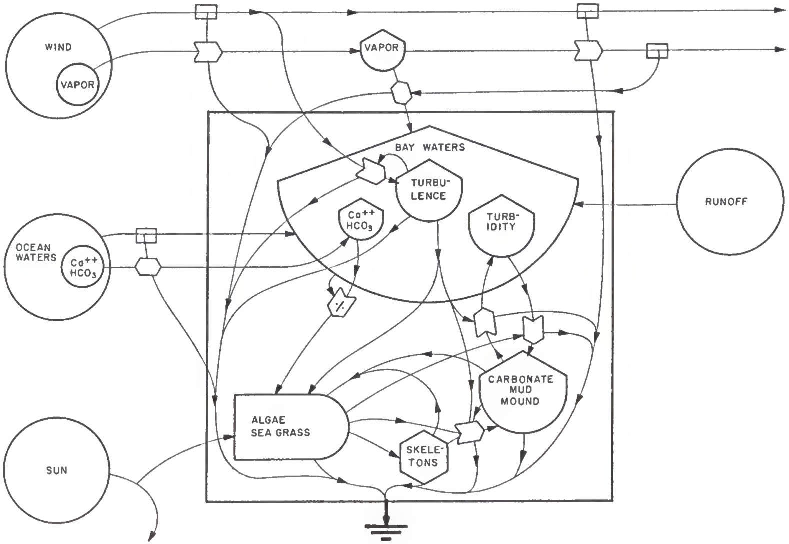


Figure 15. Energy model of a marine mud mound in Florida Bay.

Table 21. Marine mud mound case study energy signature (data on actual energy flows are given in Appendix II-I).

Energy Source	Actual Energy Flow, $Cal/m^2 \cdot yr$	Energy Transformation Ratio, solar Cal/Cal	Embodied Energy Flow, 10^6 solar $Cal/m^2 \cdot yr$
Sun	1,500,000	1	1.5
Wind	650	74	0.05
Chemical potential of runoff	2,300	3,600	8.3
Tide	49.4	3,200	0.2
Total embodied flow			8.5

Embodied Energy in Spoil Mound Form

A model of a spoil mound is shown in Figure 16. The main energy inputs come from the dragline (controlled by mining decision) and natural energies such as sun, wind, seeds, and rain. Components of the spoil mound are the ecosystem growing on the mound and land area, which includes mound form and small gullies. After initial input from the dragline, mound form interacting with rain generates small gullies down the face of the mound surface through erosion. These gullies may be important in providing germination sites with ameliorated microclimate for colonizing vegetation. Gullies seem to accelerate initial development of ecosystem biomass, which later spreads outside the gullies to the rest of the mound surface. The biomass in turn controls runoff and thus stabilizes the system. The embodied energy of the mound landform is used over long periods of time, interacting with the succession of ecosystem to build and maintain structure.

Embodied energy of a spoil mound was calculated as a by-product of the mining process. The energy signature of a spoil mound in the central Florida phosphate district is given in Table 22. The largest energy inflow is from the energy used by the dragline in mining out the phosphate matrix. Energy input to the dragline is 30 times greater than the natural energy signature, making it the dominant feature of the landscape. The role of the dragline is as a large consumer—reorganizing, recycling, and even creating new land. Since the main purpose of the dragline is mining and not the construction of spoil mounds, the mounds are actually a by-product of mining. The embodied energy used to mine the matrix and thus build spoil mound structure was found to be 2.0×10^{10} solar Cal/mound or 1.7×10^{7} solar Cal/m^2.

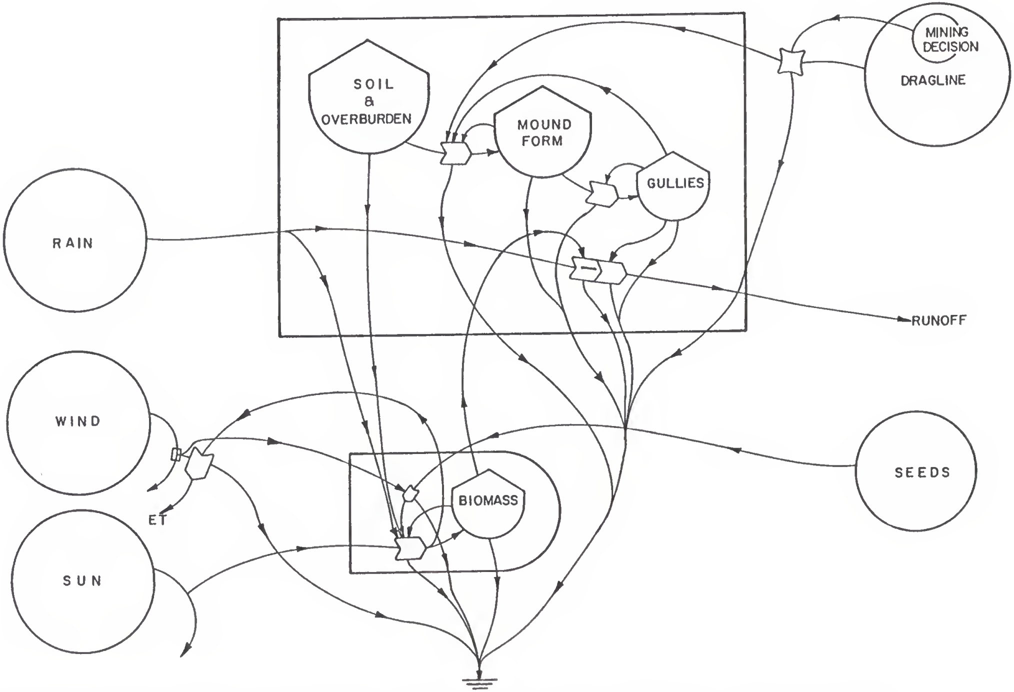


Figure 16. Energy model of a spoil mound formed by the action of mining for phosphate matrix.

Table 22. Spoil mound case study energy signature (data on actual energy flows are given in Appendix II-J and footnotes below).

Energy Source	Actual Energy Flow, $Cal/m^2 \cdot yr$	Energy Transformation Ratio, solar Cal/Cal	Embodied Energy Flow, 10^6 solar $Cal/m^2 \cdot yr$
Sun	1,500,000	1	1.5
Wind	600	74	0.04
Chemical potential of rain	3.9	3,600	0.01
Elevated potential of runoff	1.5	3,000	0.004
Kinetic impact of rain	9.0	240,000	2.1
Dragline	---	---	68.0[a]
Total embodied flow			68.6

[a] Inputs to dragline to build a spoil mound: Inputs to a 35 cubic yard capacity dragline are given below from Zeindler (1964) on a cubic yard basis.

Labor = 2.6 x 10^{-3} man-hours (at \$3.17/hr), or \$8.2 x 10^{-3};
Electricity = 0.6 KWH;
Maintenance = \$0.02;
Amortized capital cost = \$9.4 x 10^{-3} (\$2 x 10^6 over 20 years).

Dragline inputs are about $\$0.04/yd^3$ for dollar costs and 0.6 KWH/yd^3 for electrical energy input. Converting these to solar energy equivalents and summing gives:

$$\begin{aligned} \text{Energy} &= (\$0.04/yd^3)(2.2 \times 10^7 \text{ solar Cal/\$}) \\ &\quad + (0.6\ KWH/yd^3)(860.5\ Cal/KWH)(8000 \text{ solar Cal/Cal}) \\ &= 8.8 \times 10^5 \text{ solar } Cal/yd^3 + 4.1 \times 10^6 \text{ solar } Cal/yd^3 \\ &= 5.0 \times 10^6 \text{ solar } Cal/yd^3. \end{aligned}$$

Using the average dimensions of a spoil mound (T. Oxford, pers. comm.)—Height = 5 m; width = 20 m; and length = 60 m—the volume of the mound can be found by assuming prism shape.

$$\begin{aligned} \text{Volume} &= (1/2) \text{ height} \times \text{width} \times \text{length} \\ &= (0.5)(5\ m)(20\ m)(60\ m) \\ &= 3000\ m^3, \text{ or about } 4000\ yd^3. \end{aligned}$$

Table 22. (continued.)

Total input to dragline in building a spoil mound is then

$$\text{Total input to dragline} = (5.0 \times 10^6 \text{ solar Cal/yd}^3)(4000 \text{ yd}^3\text{/mound})$$
$$= 2.0 \times 10^{10} \text{ solar Cal/mound.}$$

Expressed on an area and volume basis this is

$$\text{Unit area input to dragline} = (2.0 \times 10^{10} \text{ solar Cal/mound})/(1200 \text{ m}^2\text{/mound})$$
$$= 1.7 \times 10^7 \text{ solar Cal/m}^2.$$

$$\text{Unit volume input to dragline} = (2.0 \times 10^{10} \text{ solar Cal/mound})/(3000 \text{ m}^3\text{/mound})$$
$$= 7.0 \times 10^6 \text{ solar Cal/m}^3.$$

Total overburden and matrix removed in the annual operation of a typical mine is 22 million cubic yards (Wang et al. 1974). Total energy to move this volume prorated over area of the mine is

$$\text{Dragline energy} = (5.0 \times 10^6 \text{ solar Cal/yd}^3)(22 \times 10^6 \text{ yd}^3\text{/yr})$$
$$(1/400 \text{ acres})(\text{acres}/4047 \text{ m}^2)$$
$$= 6.8 \times 10^7 \text{ solar Cal/m}^2\cdot\text{yr.}$$

Another aspect of spoil mounds that affects the energetics of mining landscapes is their surface area. Premining topography was to a large extent flat while postmining surfaces are diverse with mounds and depressions. Surface area per unit of horizontal distance is greater in the mound landscape compared to the flat premining landscape. In terms of surface area, a single spoil mound covers 1341.6 m^2 compared to a corresponding flat area of 1200 m^2 (see footnote below). In other words, there is about 10% more surface area after mining. The action of mining created new area, which may have many ramifications in terms of energy flows that are input on an area basis.

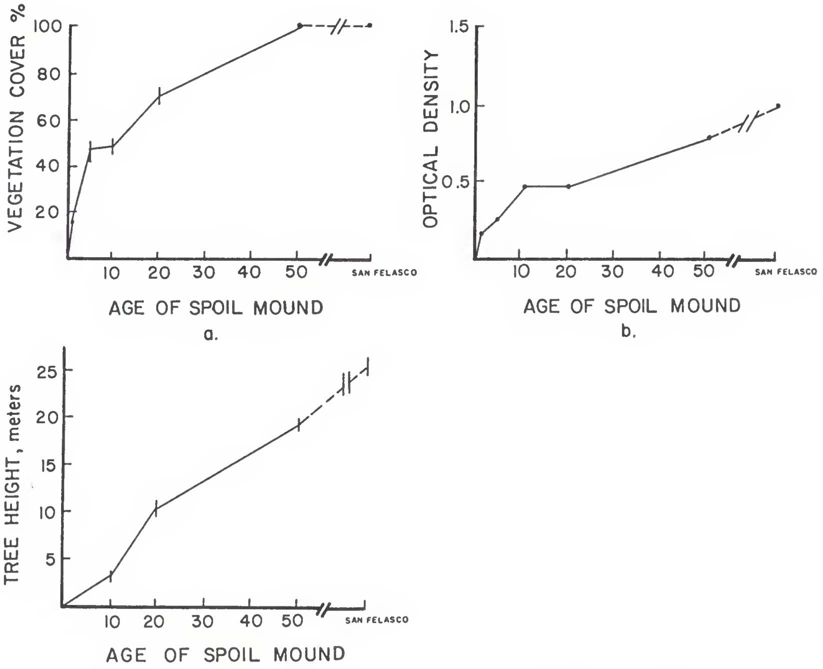
Succession on Overburden Spoil Mounds

Development of Vegetation Structure

Results of measurements of vegetation on spoil mounds are shown in Figure 17. A general increase in vegetation characteristics with time is evident in each case. Percent cover data are shown in Figure 17a. Between 1- and 5-year-old sites, cover increases dramatically from about 16% to about 47%. Little increase was found from 5 to 10 years. Cover increases to about 70% at the 20-year-old sites with bare area dispersed amongst grass stems and clumps rather than in large bare patches as at

---

Surface area of spoil mound: Assuming the mound has the geometry of a prism, the hypotenuse of the right triangle representing one half of the mound cross section is $h^2 = a^2 + b^2$ where a = 5 meters; b = 10 meters; and $h = (5^2 + 10^2)^{0.5} = 11.18$ meters. Surface area of a mound slope is then $A = (60\ m)(11.18\ m) = 670.8\ m^2$. Since the mound has two slopes as a prism, total mound surface area = $2A = 2(670.8\ m^2) = 1341.6\ m^2$.



a.

b.

c.

Figure 17. Results of measurement of successional development of vegetation structure on phosphate spoil mounds. a. vegetation cover, b. optical density, c. tree height. Bars through the means represent ± 1 standard error.

younger sites. On the oldest sites cover approaches 100% as indicated by aerial photographs. Optical density is shown in Figure 17b. The curve increases from 0.19 to 1.02 at San Felasco. This indicates increasing thickness of the canopy through succession. Variation was great at young sites due to the patchy distribution of cover but decreased with site age as cover became more continuous. Tree height data, shown in Figure 17c, increases from about 3 meters on the 10-year-old site to a maximum of greater than 25 meters at San Felasco. The increase is nearly linear with no indication of leveling at the oldest sites.

Development of Litter and Soil

Figure 18 presents data on litter, soil organic matter, and ants as an index of soil-animal activity. The general trend again is an increase over time in each case. Litter weight, shown in Figure 18a, develops quickly during the first 10 years, slows between years 10 and 20, then increases in later stages to a maximum of almost 1600 g/m^2. Litter depth or thickness data are given in Figure 18b. Litter was too sparse to measure depth at the 1-year-old site. Litter depth drops slightly between 5 and 10 years then increases gradually to the 50-year level. A large increase was found between the 50-year-old sites and San Felasco, proportionally greater than the increase in litter weight. This indicates that the litter at San Felasco has relatively more air space than at the 50-year-old site. Figure 18c shows the development of soil organic matter. After an initial drop between 1 and 5 years, soil organic matter increases to a maximum of over 8% at the 50-year-old sites then drops at San Felasco. Ant nest data for the first 10 years are shown in Figure 18d. The increase in ant nests over time is dramatic, from 2 per 10 m^2

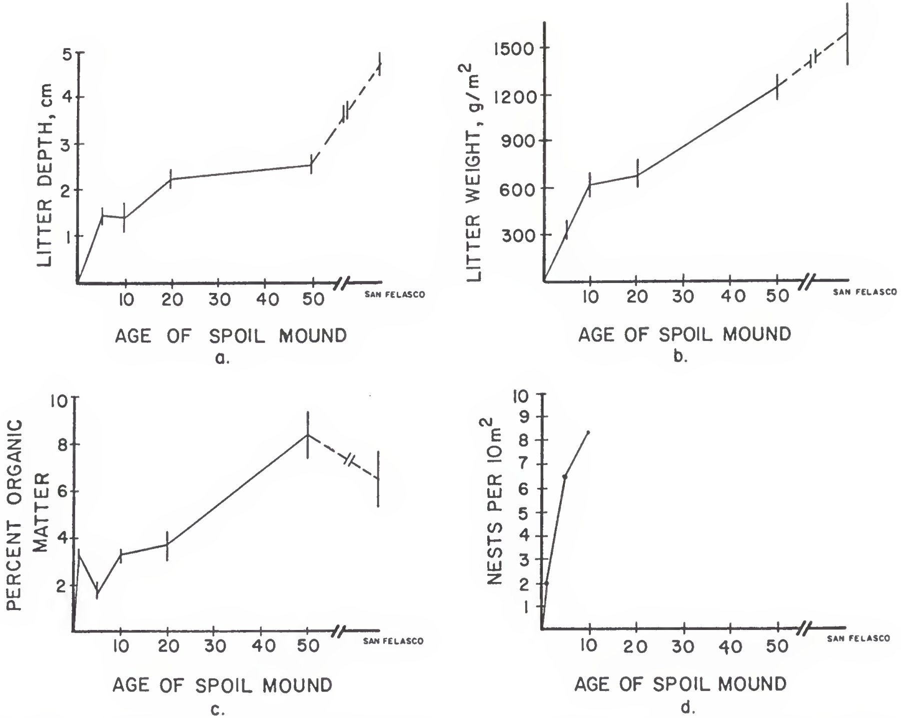


Figure 18. Results of measurements of successional development of litter and soil on phosphate spoil mounds. a. litter depth, b. litter weight, c. soil organic matter, d. ant nests. Bars through the means represent ± 1 standard error.

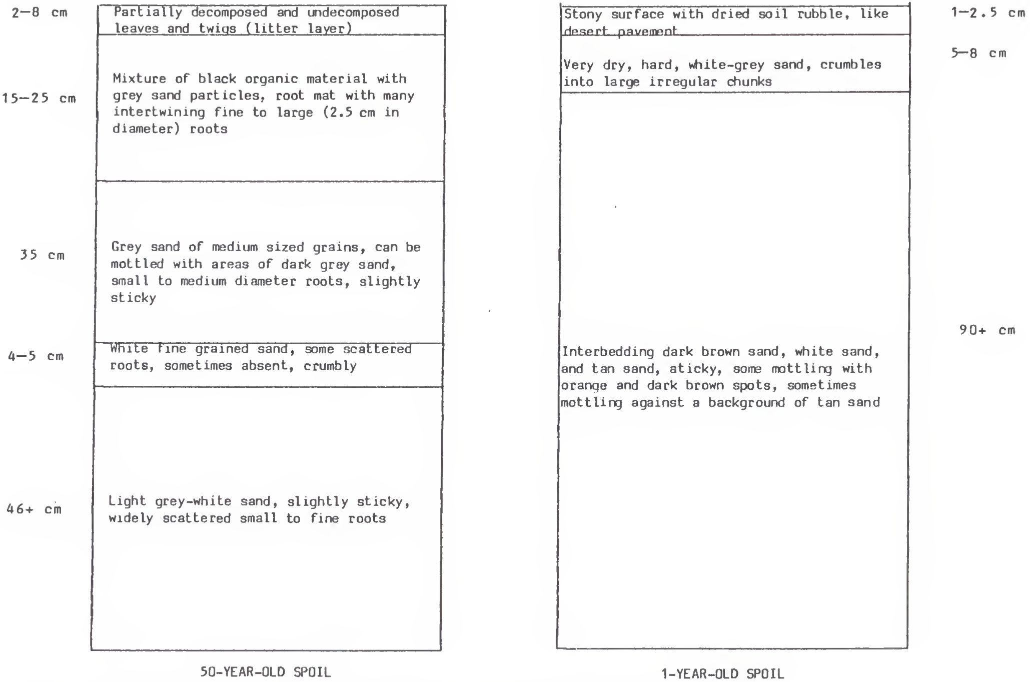
at 1 year to over 8 per 10 m^2 at the 10-year-old site. Also a general increase in ant nest size with increasing site age was noted up to the 50-year-old sites where few ants were seen.

Contrasts in soil profile development are shown in Figure 19. The 1-year-old soil has a hardened surface with little differentiation down the profile. The 50-year-old soil shows considerable development relative to the 1-year-old soil. Figure 19 shows several strata evident including litter already mentioned. Roots and organic matter are interspersed throughout the upper layers.

Forest Structure and Composition on 50-Year-Old Sites and San Felasco

Basic data of stem density and basal area for tree species plus standing dead at the two 50-year-old sites are compared in Table 23. The same species are found at both sites with moderate changes in characteristics between sites. Importance values are calculated in Table 24. Both stands are dominated by live oak, *Quercus virginiana*, with subdominates switching importance between sites.

Tables 25 and 26 give data for canopy trees (greater than 10 centimeters dbh) at San Felasco and the phosphate spoil mounds, respectively. Basal area and stem density are combined as importance values for each species. At San Felasco, 17 species (counting standing dead) were found with a total basal area of 35.4 m^2/ha and a total stem density of 602 trees/ha. Six species (counting standing dead) were found on the two 50-year-old phosphate spoil mounds with a total basal area of 28.6 m^2/ha and a total stem density of 368 trees/ha.



	50-YEAR-OLD SPOIL
2—8 cm	Partially decomposed and undecomposed leaves and twigs (litter layer)
15—25 cm	Mixture of black organic material with grey sand particles, root mat with many intertwining fine to large (2.5 cm in diameter) roots
35 cm	Grey sand of medium sized grains, can be mottled with areas of dark grey sand, small to medium diameter roots, slightly sticky
4—5 cm	White fine grained sand, some scattered roots, sometimes absent, crumbly
46+ cm	Light grey-white sand, slightly sticky, widely scattered small to fine roots

	1-YEAR-OLD SPOIL
1—2.5 cm	Stony surface with dried soil rubble, like desert pavement
5—8 cm	Very dry, hard, white-grey sand, crumbles into large irregular chunks
90+ cm	Interbedding dark brown sand, white sand, and tan sand, aticky, some mottling with orange and dark brown spots, sometimes mottling against a background of tan sand

Figure 19. Comparison of soil profiles at 1- and 50-year-old mining sites.

Table 23. Comparison of tree data at the 50-year sites.

	Payne Creek		Christina	
	Stem Density, trees/ha	Basal Area, m^2/ha	Stem Density, trees/ha	Basal Area, m^2/ha
Quercus virginiana Mill.	122	11.4	135	21.9
Quercus nigra L.	52	4.0	74	6.5
Liquidambar styraciflua L.	93	4.0	48	2.3
Pinus elliottii Engelm.	70	2.0	9	0.4
Prunus serotina Ehrh.	7	0.6	61	2.2
Standing dead	19	0.4	48	2.4
Total	363	22.4	375	35.7

Table 24. Comparison of relative parameters for trees at the 50-year sites.

	Payne Creek			Christina			
	Relative Density[a]	Relative Dominance[b]	Importance[c]	Relative Density[a]	Relative Dominance[b]	Importance[c]	Combined Frequency
Quercus virginiana Mill.	34	50	42.0	36	62	49.0	88
Quercus nigra L.	14	18	16.0	20	18	19.0	100
Liquidambar styraciflua L.	26	18	22.0	13	6	9.5	38
Pinus elliottii Engelm.	19	9	14.0	2	1	1.5	63
Prunus serotina Ehrh.	2	3	2.5	16	6	11.0	75
Standing dead	5	2	3.5	13	7	10.0	88

[a] Relative density = number of trees of a given species per area divided by the total number of trees per area.

[b] Relative dominance = basal area of a given species per area divided by the total basal area per area.

[c] Importance = (relative density + relative dominance)/2.

Table 25. San Felasco Hammock tree data. Numbers in parentheses are percentages.

	Stem Density, trees/ha	Basal Area, m^2/ha	Importance Value
Magnolia grandiflora L.	100 (16.6)	9.8 (27.7)	22.15
Liquidambar styraciflua L.	137 (22.8)	7.0 (19.8)	21.30
Tilia floridana Small	63 (10.5)	4.1 (11.6)	11.05
Quercus laurifolia Michx.	44 (7.3)	4.2 (11.9)	9.60
Ostrya virginiana (Mill.) K. Koch	78 (13.0)	1.7 (4.8)	8.90
Quercus marilandica Muench H.	19 (3.1)	4.5 (12.7)	7.90
Carpinus caroliniana Walt.	70 (11.6)	1.2 (3.4)	7.5
Magnolia virginiana L.	15 (2.5)	1.0 (2.8)	2.65
Carya glabra (Mill.) Sweet	19 (3.1)	0.6 (1.7)	2.40
Cornus florida L.	19 (3.1)	0.4 (1.1)	2.10
Nyssa sylvatica var. *biflora* (Walt.) Sarg.	11 (1.8)	0.3 (0.8)	1.30
Pinus glabra Walt.	4 (0.7)	0.3 (0.8)	0.75
Quercus nigra L.	7 (1.1)	0.1 (0.3)	0.70
Ilex opaca Ait.	4 (0.7)	0.1 (0.3)	0.50
Robinia pseudoacacia	4 (0.7)	>0.1 (0.1)	0.40
Acer rubrum L.	4 (0.7)	>0.1 (0.1)	0.40
Standing dead	4 (0.7)	>0.1 (0.1)	0.40
Total	602	35.4	

Table 26. Combined phosphate spoil mound forest tree data. Numbers in parentheses are percentages.

	Stem Density, trees/ha	Basal Area, m^2/ha	Importance Value
Quercus virginiana Mill.	128 (34.8)	16.2 (56.8)	45.80
Quercus nigra L.	62 (16.8)	5.1 (17.9)	17.35
Liquidambar styraciflua L.	72 (19.6)	3.2 (11.2)	15.40
Pinus elliottii Engelm.	42 (11.4)	1.3 (4.6)	8.00
Prunus serotina Ehrh.	32 (8.7)	1.3 (4.6)	6.65
Standing dead	32 (8.7)	1.4 (4.9)	6.80
Total	368	28.5	

Standing dead trees have low importance values but are a constant feature of the forests as indicated by the frequency data. They may play important functional roles in forest ecology in terms of wildlife habitat and nutrient conservation (Egler 1975; Bormann and Likens 1979). Importance values of dead trees at the 50-year-old sites was 17 times greater than at San Felasco, perhaps reflecting that the tree community of the phosphate forest has gone through more recent transitions and is not yet at steady state.

Simulation of Succession

The succession model with data used for evaluation of coefficients is shown in Figure 20. Storage units are g dry weight/m^2 and flow units are g dry weight/$m^2 \cdot yr$. References and derivations are given in Appendix III and the program in included as Appendix IV. The standard simulation run of succession is given in Figure 21a. Grasses peak first, after about 5 years; pines dominate next from about 10 to 40 years; climax hardwoods supplant pines and reach steady state at about 60 years; and litter gradually builds to a steady state after about 50 years. This general pattern of vegetation change fits the field observations summarized in the discussion.

Table 27 provides validation of the model by comparing predicted litter biomass, run at different time integration intervals, with litter biomass from field sampling of phosphate mine ecosystems (see Figure 18b). With time steps of 0.25 years and 0.1 years, only the predicted 5- and 50-year litter values fall within the standard error limits of observed litter. With a time step of 0.025 years, the predicted 20-year litter

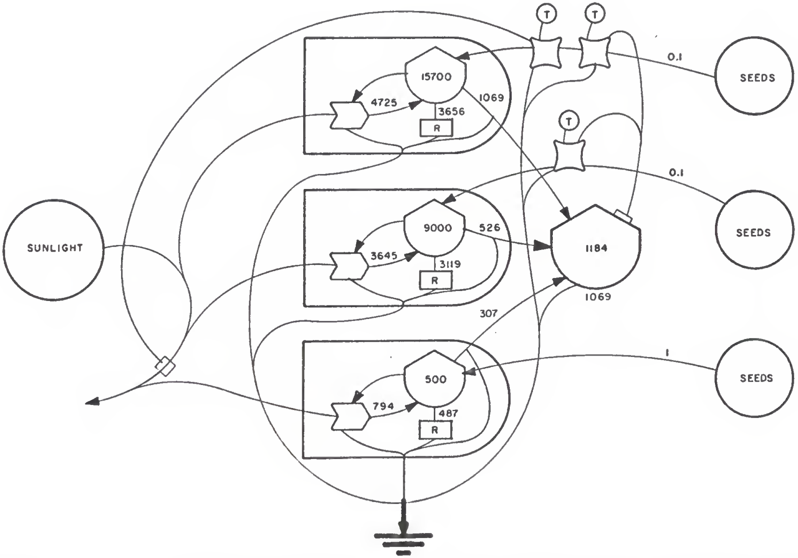


Figure 20. Succession model with data used to calculate coefficients. Storages are in g organic matter/m^2 and flows are in g organic matter/m^2·yr. Calculations are as included in Appendix IV.

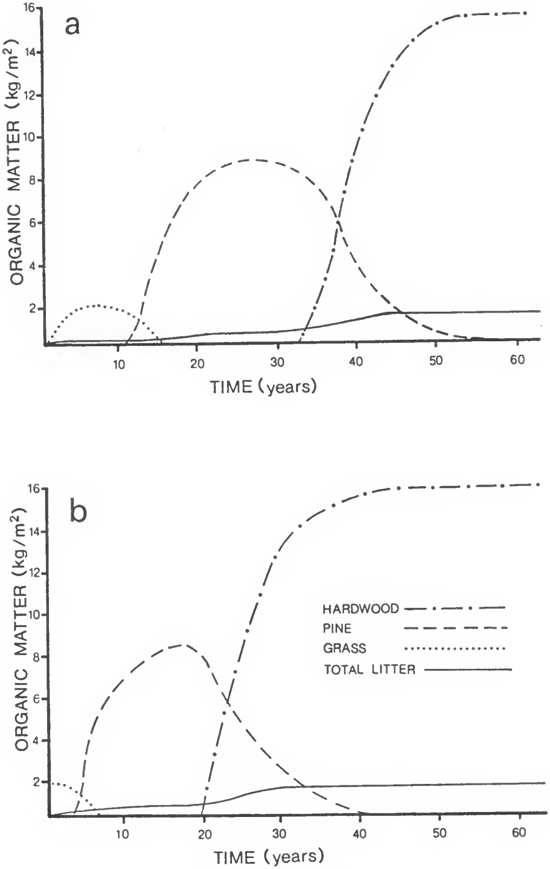


Figure 21. Comparison of the effects of increasing the seeding rate on the rate of succession. a. standard run, b. result of increasing the seeding rate 1000 times after the litter germination thresholds are reached. Grass vegetation biomass, Q_3, is scaled by 4 times to excentuate its growth curve.

Table 27. Comparison of litter values from simulation runs with varying time steps (DT), with litter data from field sampling for validation.

T, yr	Q4(DT=0.25)	Q4(DT=0.1)	Q4(DT=0.025)	Q4(DT=0.01)	Measured Litter
1	4.0	12.4	36.6	61.8	54.0 ± 11.8
5	309.0	317.5	340.0	375.2	377.2 ± 61.6
10	341.0	342.3	369.7	342.8	622.8 ± 71.5
20	524.5	557.2	604.3	668.9	688.5 ± 96.7
50	1196.8	1223.13	1257.4	1300.5	1250.4 ± 73.1

also fits the data. Best fit of predicted values with those observed was found with a time interval of 0.01 years, for which all predictions except the 10-year value fell within acceptable variation. Due to the magnitude of the scaling factors and length of simulation runs (70 years), however, these changes in precision did not greatly effect the form of the simulation graphs. Therefore, simulation graphs were plotted with a time step of 0.25 years since this ran much faster.

Two principal types of simulations were performed with the model: increasing seeds as a pulse after germination thresholds were reached and adding litter. The performance of these experiments on the model are summarzied in Table 28. Performance was judged by the age at which hardwood steady state was reached. All simulations with seed additions had the same pattern of growth and transition of vegetation as the standard or control run shown in Figure 21a. Succession was accelerated from 5% to 25% by this type of simulation. As an example the run with all seeds being pulsed 1000 times is shown in Figure 21b. Relative to the control run, the first two stages in succession are abbreviated even though they still reach comparable peak biomass values as in the control succession. Climax is reached in year 44, which is 12 years faster than in the control.

The effects of adding litter with and without light threshold on hardwood germination are shown in Figure 22a and 22b, respectively, and also in Table 28. With the light control, no addition of litter caused significant change in succession, since hardwood germination was being limited by light, not litter. Tests run on the model without the light control showed that the optimal litter addition was 300 g/m^2 on year 5 of succession. This strategy allowed the fast growing grass stage to

Table 28. Comparison of performance of simulation experiments in accelerating succession.

Simulation Description	Age of Climax, yr	Percent Acceleration
Standard run	59	--
Pulse grass seed by 1000	56	5
Pulse pine seed by 1000	54	9
Pulse hardwood seed by 1000	52	12
Pulse pine and hardwood seeds by 1000	47	20
Pulse all seeds by		
1000	44	25
100	51	14
10	56	5
Add litter w/light control	59	0
Add litter w/o light control	41	31
Pulse all seeds by 1000 and add litter	33	44

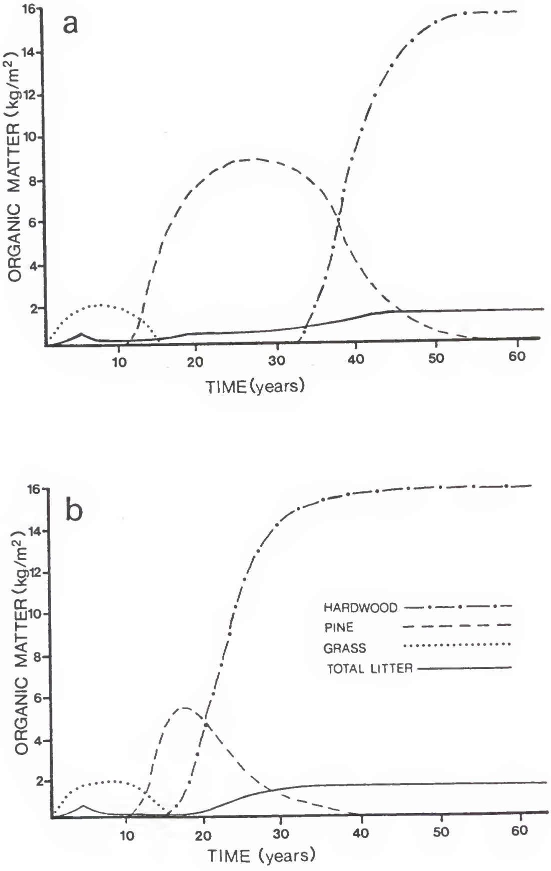


Figure 22. Comparison of the effects of the light threshold on litter additions to the simulation model of succession. a. addition of litter with the light control threshold, b. addition of litter without the light control threshold. Grass vegetation biomass, Q_3, is scaled by 4 times to excentuate its growth curve.

develop its peak litter biomass to which the minimum amount of litter was added to initiate germination of hardwoods. This experiment shortened the pine stage and decreased its peak biomass, perhaps since its role in succession was taken up in part by the litter addition. Climax is reached in year 41, which is 3 years faster than in the seeding experiments and 18 years faster than the control simulation.

A final simulation combined the addition of seeds and litter without the light control on hardwood germination to view the maximum amount that succession may be able to be accelerated. This run is shown in Figure 23b. The general pattern of succession is similar to that found with the addition of litter (Figure 22b). However, climax is reached by year 33, which is 44% faster than in the standard or control.

Energy Analysis of Reclamation Alternatives

Many unreclaimed spoil mounds of various ages are scattered throughout the central Florida phosphate district left from past mining. Reclamation of these and recently produced mounds often consists of leveling the spoil mounds and planting pasture grasses. However, in many cases succession has filled the role of reclamation through the development of ecosystems on the abandoned mines. An important issue for state and local governments is to decide whether these old mined lands need to be reclaimed. One way this problem can be approached is by comparing embodied energy in the two reclamation alternatives.

A phosphate mining model is shown in Figure 24. This model does not describe the entire phosphate production industry but emphasizes land reclamation alternatives, including putting land into pasture through

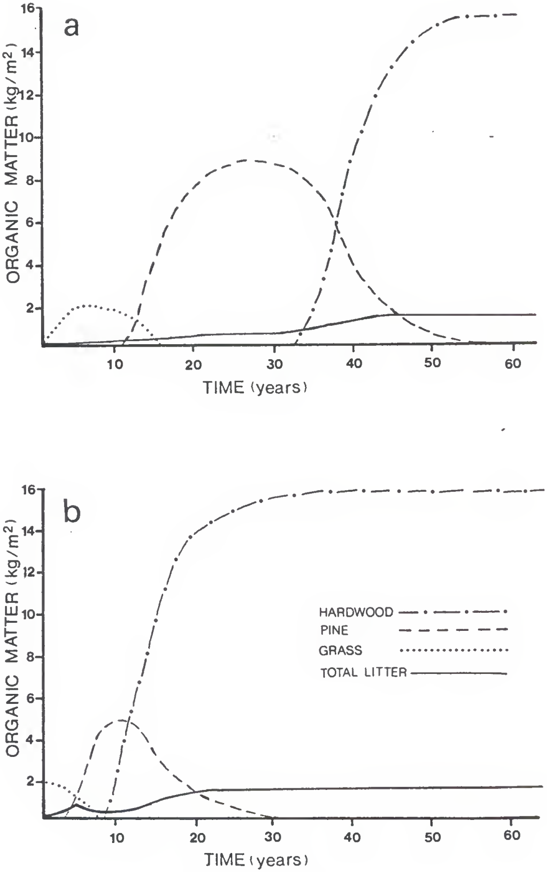
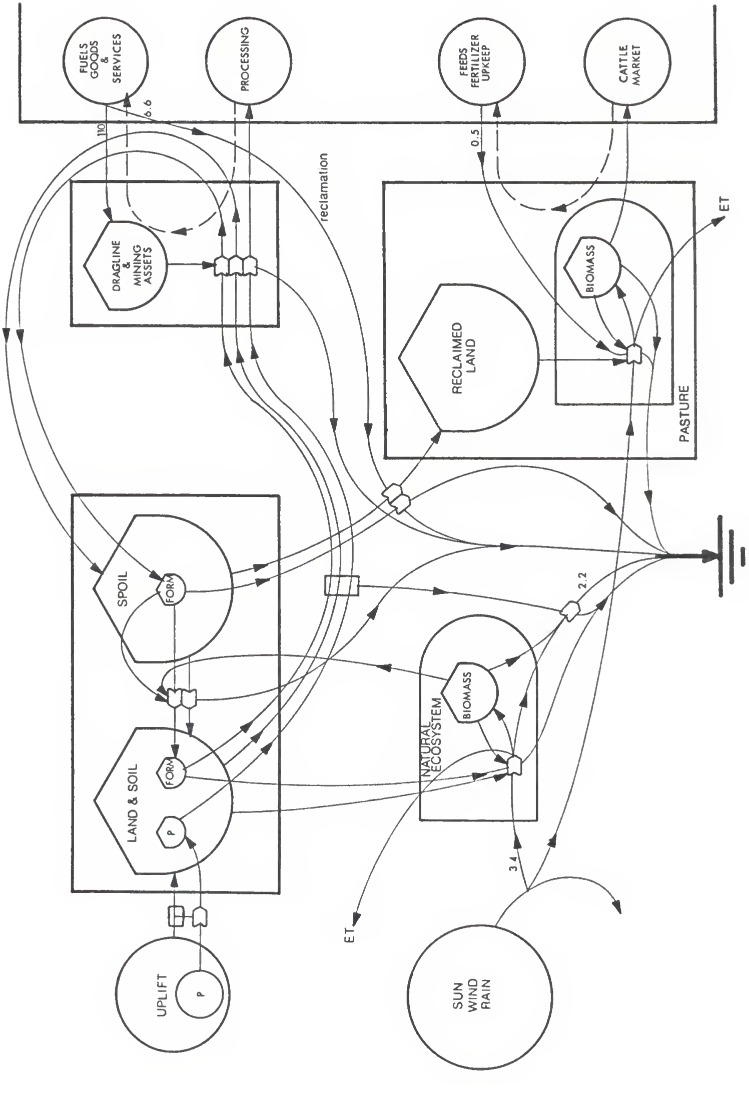


Figure 23. Comparison of the effects of increasing the seeding rate and addition of litter on the rate of succession. a. stand run; b. result of increasing seeding rate 1000 times and adding litter. Grass vegetation biomass, Q_3, is scaled by 4 times to excentuate its growth curve.

Figure 24. Energy model of a phosphate mine for comparison of reclamation alternatives. Numbers are x 10^{12} solar Cal/mine·yr.


FUELS GOODS & SERVICES
PROCESSING
FEEDS FERTILIZER UPKEEP
CATTLE MARKET
110
6.6
reclamation
0.5
DRAGLINE & MINING ASSETS
RECLAIMED LAND
BIOMASS
PASTURE
ET
SPOIL
FORM
FORM
LAND & SOIL
P
NATURAL ECOSYSTEM
BIOMASS
2.2
3.4
ET
UPLIFT
P
SUN WIND RAIN

conventional reclamation versus natural succession restoring the ecosystems. The extraction of the phosphate matrix is shown as being exported for further processing. The model is based on the annual operations of a representive mine with 400 acres of active mining. Embodied energy flows are shown as 10^{12} solar Cal/mine·yr. The results of the calculations are summarized in Table 29.

The embodied energy equations describing the two reclamation alternatives are set up as an equality in Figure 25. The age of spoil mound that satisfies the equality is then solved for by rearranging the equations and substituting the calculated values from Table 29. This solution represents the threshold age of an unreclaimed mound that has more embodied energy from succession than could be generated by mechanical reclamation. This threshold was found to be at age 16 years. Conventional reclamation of mined lands of this age and younger could yield an embodied energy savings, but on older lands it would yield less embodied energy than it consumes. If the end land use is taken to be improved pasture the cost of leveling the spoil mounds is \$750/acre (Wang et al. 1974). Without mining the cost of clearing and preparing the land for pasture is \$136/acre (see footnote below). Therefore more than \$600/acre in additional costs are required to develop pasture on mined land versus unmined land. This difference makes the payback period longer for cattle operation on reclaimed mined lands. However, improved pasture may be the best landuse in the long run for reclaimed land from the mining industry's perspective since it generates economic return. Natural succession generates no direct

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Cost of clearing and preparing land for improved pasture: Bulldozer costs, \$542/day (Godfrey 1976) divided by 4 acres cleared/day (Ruess 1958).

Table 29. Embodied energy flows in Figure 24.

Flow	Embodied Energy 10^{12} solar Cal/mine·yr	Footnote
Natural input (sun, wind, rain)	3.4	a
Lost productivity	2.2	b
Energy in reclamation	6.6	c
Inputs to dragline	110.0	d
Pasture subsidy	0.5	e

[a] Natural energy input: The natural energy portion of the energy signature for a spoil mound is 2.1×10^6 solar Cal/m^2·yr (Table 22). Expressed over the area of the mine the energy equivalent is

$$\text{Energy} = (2.1 \times 10^6 \text{ solar Cal/m}^2\cdot\text{yr})(400 \text{ acres})(4047 \text{ m}^2\text{/acre})$$

$$= 3.4 \times 10^{12} \text{ solar Cal/yr.}$$

[b] Energy in lost productivity: As a consequence of mining, gross primary productivity is lost over the length of time needed to return to past levels. Using productivity of pineland from Costanza (1975) and approximating total loss as one-half of this rate for 20 years of succession, the energy equivalent is

$$\text{Energy} = (5.5 \times 10^6 \text{ coal Cal/acre}\cdot\text{yr})(2000 \text{ solar Cal/coal Cal})(400 \text{ acres})(0.5)$$

$$= 2.2 \times 10^{12} \text{ solar Cal/yr.}$$

[c] Energy in reclamation: The costs of phosphate mine reclamation are \$750/acre (Wang et al. 1974). The energy equivalent expressed over the area of a typical mine is

$$\text{Energy} = (\$750\text{/acre})(2.2 \times 10^7 \text{ solar Cal/\$})(400 \text{ acres/yr})$$

$$= 6.6 \times 10^{12} \text{ solar Cal/yr.}$$

[d] Dragline inputs: Dragline inputs were calculated in the footnote to Table 22 at 5×10^6 solar Cal/yd^3. Total overburden and matrix removed in the annual operation of a typical mine is 22 million yd^3 (Wang et al. 1974). Total energy equivalent is

$$\text{Energy} = (22 \times 10^6 \text{ yd}^3\text{/yr})(5 \times 10^6 \text{ solar Cal/yd}^3)$$

$$= 1.1 \times 10^{14} \text{ solar Cal/yr.}$$

Table 29. (continued.)

[e] Pasture subsidy: Costanza (1975) gives the fossil fuel subsidy to improved pasture at 6.29×10^5 coal Cal/acre·yr. Expressed for the mine area the energy signature is

$$\text{Energy} = (6.29 \times 10^5 \text{ coal Cal/acre·yr})(2000 \text{ solar Cal/coal Cal})(400 \text{ acres})$$

$$= 0.5 \times 10^{12} \text{ solar Cal/yr.}$$

Embodied energy of unreclaimed spoil mound = (age of mound x embodied energy input) - (lost productivity x length of succession)

Embodied energy of pasture = reclamation + [(upkeep subsidy + embodied energy input) x length of succession]

Embodied energy of spoil mound = embodied energy of pasture

(age of mound x embodied energy input) - (lost productivity x length of succession)

= reclamation + [(upkeep of subsidy + embodied energy input) x length of succession]

(age of mound x embodied energy input) = reclamation + [(upkeep subsidy + embodied energy input) x length of succession]

+ (lost productivity x length of succession)

$$\text{age of mound} = \frac{\text{reclamation} + [(\text{upkeep subsidy} + \text{embodied energy input}) \times \text{length of succession}] + (\text{lost productivity} \times \text{length of succession})}{\text{embodied energy input}}$$

$$\text{age of mound} = \frac{6.6 \times 10^{12}\ \text{Cal} + [(0.5 \times 10^{12}\ \text{Cal/yr} + 3.4 \times 10^{12}\ \text{Cal/yr}) \times 1\ \text{yr}] + (2.2 \times 10^{12}\ \text{Cal/yr} \times 20\ \text{yr})}{3.4 \times 10^{12}\ \text{Cal/yr}}$$

$$\text{age of mound} = \frac{54.5 \times 10^{12}\ \text{Cal}}{3.4 \times 10^{12}\ \text{Cal/yr}}$$

age of mound = 16 yr.

Figure 25. Calculation of age of unreclaimed mound at which embodied energy in mechanical reclamation equals embodied energy in succession.

value but its indirect values of restoring fertility and as wildlife habitat may be significant.

Phosphate Fertilizer Industry Model

A model of the Florida phosphate fertilizer industry is shown in Figure 26. The overall industry is depicted as a main circuit of phosphate flowing from the landscape to the fertilizer market. The process is initiated and maintained by a switch, which senses the amount of phosphate in the matrix. Mining will only take place if sufficient deposits are anticipated. The industry is shown with two main parts, the mine itself and the fertilizer plant. Economic exchange is with the fertilizer market in the outside economy. Inputs to the industry include water, matrix, capital investment, and goods, services, and fuels. Water is mostly recycled. The mine includes strip mining by draglines, which remove overburden spoil and expose the matrix, water flows, which are used to transport the matrix and wastes as a slurry in pipes, and the beneficiation plant where matrix is separated into sand, clay, and phosphate, which is sent to the fertilizer plant. There the phosphate is mixed with sulfuric acid, upgrading the phosphate rock to produce commercial fertilizer. Gypsum is a by-product waste of this process. Reclamation is shown as an "upstream" circuit restoring spoil, sand tailings, and slime clays. This includes land manipulation, such as grading and diking, plus some revegetation. Gypsum is not reclaimed, but is left stacked next to the fertilizer plant.

An aggregated model of the phosphate fertilizer industry is shown in Figure 27. This model is evaluated for cost of mining and processing

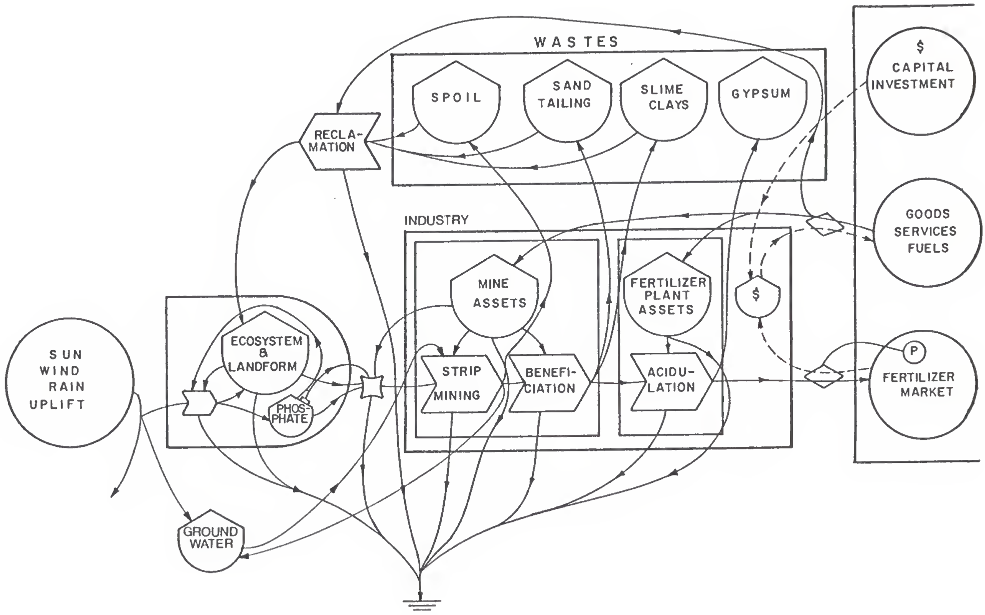


Figure 26. Detailed model of the phosphate fertilizer industry.

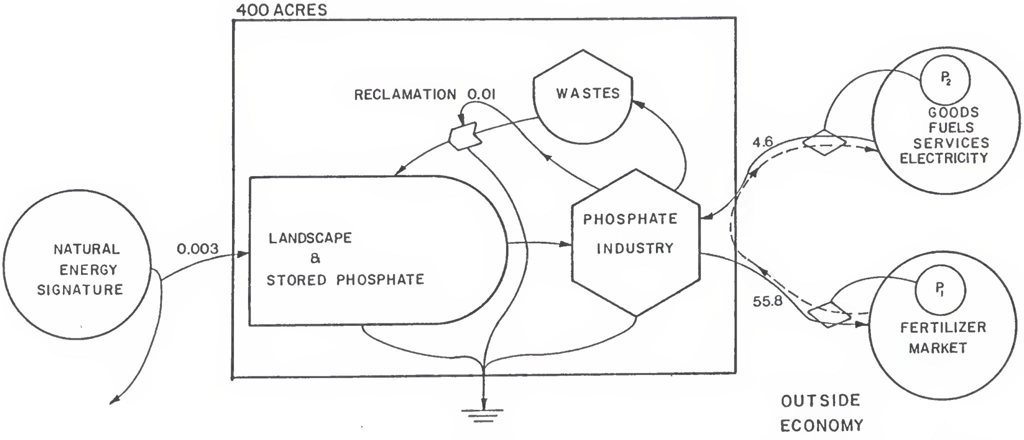


Figure 27. Energy model of a typical phosphate mining and fertilizer operation. Values are x 10^{15} solar Cal/yr. Economic exchanges are shown controlled by price function, P_1 and P_2. Calculations are given in Appendix V.

phosphatic matrix into phosphoric acid fertilizer, on the basis of a single typical industry unit. Total costs are 4.6×10^{15} solar Cal/yr for an annual fertilizer output of about 1.2×10^6 tons. In the annual production of fertilizer, 2.4×10^7 tons of waste land material (about 20 tons of waste/ton fertilizer) are created (see footnote below). Reclamation of these waste lands requires 1.4×10^{13} solar Cal. This model illustrates the relative magnitude of reclamation in terms of the total budget. Reclamation is 0.3% of the total, showing that its overall cost is very small. Calculations of these numbers are given in Appendix V.

Essentially all of the embodied flow of fertilizer to market is net energy (55.8 - 4.6), which has a yield ratio of 12 solar Cal output per solar Cal of input. These large values are the result of mining a rich, nonrenewable storage.

Waste volumes generated in the production of fertilizer. Spoil: 13,000,000 yd^3 (EPA 1978)/5×10^6 ton of rock (Greene 1978) = 2.6 yd^3/ton of rock; (2.6 yd^3/ton of rock)(3.31 ton of rock/ton of fertilizer)(Phillips 1975) = 8.6 yd^3/ton of fertilizer. Assume density of spoil as 1.4 g/cm^3. [(8.6 yd^3/ton)(0.7646 m^3/yd^3)(10^6 cm^3/m^3)(1.4 g/cm^3)(kg/1000 g)]/(10^3 kg/ton) = 9.2 tons. Clay: One ton of clay is removed for each ton of rock (EPA 1978) (1 ton clay/1 ton rock)(3.31 ton rock/ton of fertilizer) = 3.31 tons. Sand: Same as clay (EPA 1978); 3.31 tons. Gypsum: 4.5 tons (Bowers 1968). Total wastes = 20.32 tons/ton of fertilizer. Total production of fertilizer is 1.2×10^6 tons/yr, making production of wastes = (1.2×10^6 tons/yr)(20.32 tons/ton) = 2.4×10^7 tons/yr.

CHAPTER 4
DISCUSSION

Energy Causality of Landscape

Energy has been suggested as the basis for causal action in all levels and kinds of real systems. Theories, models, and calculations have been given here for the energy causality of landscape. A theory of the spatial expression of energy sources and the complementary shapes they cause to develop in landscape components is central in these explanations. The theory as given here states that the pattern of incoming energies interacting with a surface builds forms on the surface, which amplify the spatial program of energy. This amplification is expressed in the convergence and divergence of energies as they flow across a landscape. For example, the form of a valley causes runoff on its slopes to converge into a central river channel. Without the valley form the power in runoff would be less focused or concentrated and thus the form has amplified the energy flow.

Because landscape itself is a map of accumulated effect of its historical energy inputs and transactions, the patterns can reveal something about how energies are used. One hypothesis is that the proportion of a landform type is directly related to the proportion of its matching spatial energy type in the energy signature of the landscape. This hypothesis is tested by calculating energy signatures for three landscapes dominated by single landform types and one landscape with a complex pattern of overlapping landform types. If the energy input algorithm and the energy quality factors are correct, for the first three landscapes the dominant spatial energy type should match with that indicated by the dominant landform type. In the fourth case, no single spatial type of energy should predominate.

The landscapes, all from Florida, have been studied with construction of maps and energy signatures. The Green Swamp area in central Florida is dominated by cypress domes, which are circular to irregularly shaped depression wetlands scattered in pine flatwoods. Brown (1978) and Odum (1978) discuss the role of these wetlands in the landscape. In this example, the cypress domes are predicted as center shapes generated by convergence of sheet energies from the background of pine flatwoods. A sheet energy should then dominate this energy signature. An energy signature for the Green Swamp is given by McCuller (1975). The Apalachicola River basin is located in the Florida panhandle and extends north into Georgia. The dominant feature of this landscape is the floodplain forest along the river and is reflective of line energy, which dominates this energy signature. An energy signature for the Apalachicola region is given by Boynton (1975). The Florida coral reef is a barrier reef extending along the Atlantic side of the Florida Keys. This is predicted as a zone shape and the energy signature is shown in Table 8 (see page 49). The dominant energy in this energy signature should be frontal type. Hendry County, in southwest Florida, is the final landscape considered. It is dominated by a variety of wetlands: cypress strands and plains, extensive marshes bordering lake Okeechobee, and scattered seasonal wet prairies and marshes. This is used as an example of a complex landscape with several shape types with no one type dominant. Thus, no dominance should occur in the energy signature by specific spatial type. An energy signature for Hendry County is given by DeBellevue (1975).

A summary of the energy signatures is given in Table 30 by their spatial type. The predictions hold for the Apalachicola Basin and the Florida coral reef. Line dominance is 80 times for the floodplain landscape and frontal dominance is more than 1000 times for the coral reef. For the Green Swamp, a sheet energy is the largest energy but it is only slightly larger than the maximum frontal energy. For Hendry County maximum sheet energy was about 2 times as large as the maximum frontal energy, which may be similar enough in magnitude to mix form types into a composite.

Most landscape are combinations of the basic form types blended together with no single type dominant as with Hendry County. In these cases the ratio of form types may not be directly proportional to the ratio of spatial energies but may be more a function of the way the energies interact. Unraveling composite patterns is the key to understanding landscape. Comparative study of different landscapes and their energy signatures may reveal interaction functions of different energies.

Energy and the Shape of Landforms

Landform has been defined as an energy storage of landscape in terms of volume, either in depressions or elevations. This was quantified by knowing the relative dimensions of the volume and by assuming some geometric shape. Why are landform shapes different? It is proposed here that energy is used more effectively when shape matches the spatial expression of energy input. Energy builds the structures and thus controls the shape

Table 30. Maximum embodied energy within energy signatures of four Florida landscapes according to spatial expression. Values are expressed x 10^6 solar Cal/m^2·yr.

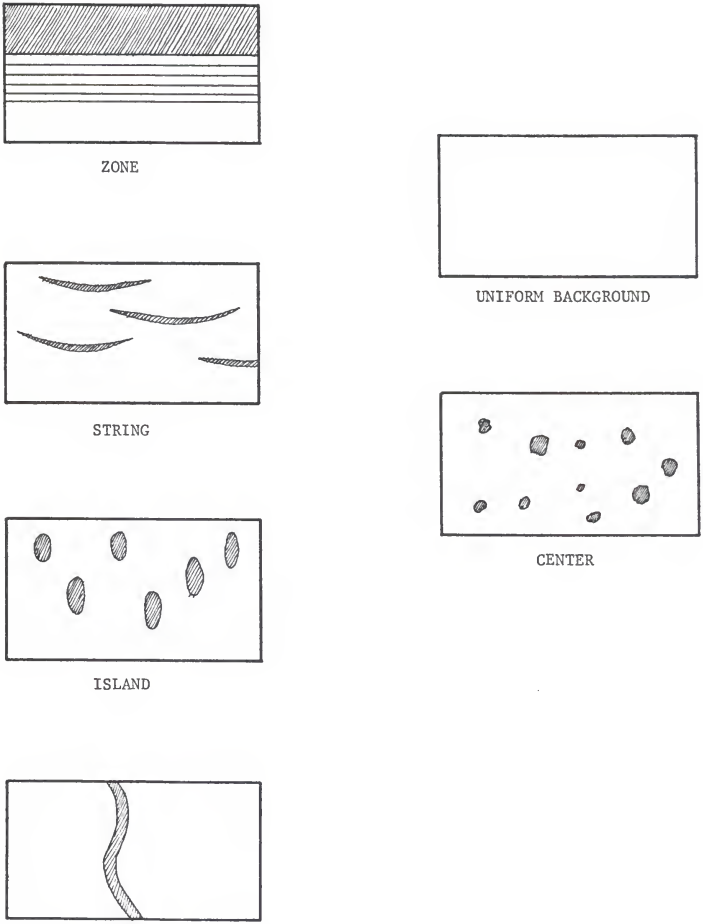
	Green Swamp	Apalachicola Basin	Florida Coral Reef	Hendry County
Maximum sheet energy[a]	1.4	1.4	1.4	1.4
Maximum frontal energy	0.9[b]	3.7[c]	1800[d]	0.6[e]
Maximum line energy	---	310[f]	---	---

[a] Sunlight.
[b] Wind.
[c] Physical runoff.
[d] Waves.
[e] Chemical runoff.
[f] River head.

of the structures. Special shapes may aid in capturing, absorbing, and possibly using energy inputs. These shapes are believed to be adaptive to specific spatial energy distributions. Evidence in the preceding section in part supports this idea, when one spatial energy type dominated an energy signature the corresponding shape-type dominated the landscape. If a certain shape allows more control, as measured in Figure 1 (see page 2) by the feedback pathway into the production function, it can be "selected for" in competition with landform alternatives of other shapes.

Shapes of landforms can aid in concentrating energies such as flows of water, wind in desert, and waves and tides on coasts. Sheets can be concentrated to form points, and fronts can be concentrated to form lines. Once concentrated, the new energies interact and converge other less concentrated energies from their surroundings. Energy lines cause a linear convergence and energy points cause a radial convergence, which helps maintain the structure they build. If the concentrated point or line does not find enough energy with which to match or interact, it will disperse. For example, consider the upper end of a watershed catchment where runoff moving as a front coverges to form a concentrated line in the form of river flow. The line collects more energy as it proceeds downslope until it reaches the coastal plain where the energy gradient decreases and the line must disperse back into a front as the river forms a delta or wide anastomosing floodplain. Concentrated sources can be insulated for some purposes, but often at great cost. An example is a channelized river.

A classification of landscape types is proposed based on the spatial expressions of energy (Figure 28). Implied is that special forms develop in response the particular spatial energy types. Based on study of maps, six basic categories of form are proposed: background, center, zone,



ZONE

UNIFORM BACKGROUND

STRING

CENTER

ISLAND

STRIP

Figure 28. Patterns of structure postulated to result from energy inflow patterns. Names of the dominant landscape form type are given to the left (see Table 31).

linear strip, transverse string, and streamlined island. These are common shapes of land surface recognizable on vegetation and land use maps. Different forms are distinguished by their shape, orientation and to some extent relative size (Table 31). This has similarities to a shape classification of Florida wetlands (Wharton et al. 1976), which recognized linear, broad basin, and circular (including irregular types) shapes in relation to water flows. Odum (1978a) presented a related series of wetlands whose form changes along a gradient of increasing water flows.

Several hypotheses relate landform to sources as follows: recurring patterns of form arise under similar external energy conditions. The forms are organizational arrangements for energy use. Spacing may be directly related to the absorption and dissipation of energy. The spacing of individual energy-absorbing forms may be important in organizing the larger patterns. If spacing is too close, competition for energy may occur, and if spacing is too great, some energy may pass without use.

Landscape shape also changes along hierarchies of converging energy. Central place type hierarchies are well known and represent the concentration of sheet energy over broad areas into center structures that perform services for the surrounding region.

Lateral hierarchy develops where energies concentrate in relation to frontal energies. The sequence in this hierarchy is suggested in Figure 4 progressing, with increasing energy, from zones to strips. An example is a watershed where the slopes capture and laterally focus water to a strip, which is the river channel. Strings and islands fall within this ideal hierarchy under certain intermediate conditions of energy. It is hypothesized that at low flows, landforms are arranged as strings that maximize the area exposed to the flows. As the flow increases, the strings rotate

Table 31. A classification of landscape form.

Form	Shape	Orientation to Energy	Examples
Strip	Linear	Parallel	River channel, commercial highway
Island	Ovoid, curved, or pointed	Pointed in direction of energy	Tree islands, transverse sand dunes
String	Linear	Perpendicular	String bog, oyster reef, longitudinal sand dunes
Zone	Rectangular or bandlike	Perpendicular	Zones of vegetation around lakes and up mountain sides, Von Thunen agricultural zone around cities
Center	Circular to irregular	Centrally located	Cypress dome wetlands, central place cities
Uniform	Undifferentiated	No orientation	Uniform plains, rural areas

90° to minimize the area directly exposed to the flow. Examples are desert dunes and some peat mounds in wetlandscapes.

The storages in central place and "lateral place" hierarchies may have the same embodied energy distribution but the shapes of the structures differ because of the generic difference of source energy input, either parallel or perpendicular to the surface.

An advantage of the shape classification is that it may allow a view of a class of emergent properties not recognized before. Ecologists have studied in detail the ecosystem adaptations for assimilating sunlight, such as chlorophyll content, assimilation number, photic zone thickness, and leaf area, some of which are recognized as emergent or summary properties. However, these apply only to one of the energy sources utilized by ecoystems (sunlight). Energy signatures are composed of other energy sources (auxiliary energies or energy subsidies) that have been shown in many cases to be of greater magnitude than direct sunlight. Landform may be a synoptic ecosystem adaptation for assimilating auxiliary energies. The recognition of different landform shapes is a step toward investigating the ways landscapes capture and assimilate energy sources. Probably few land systems are developed with sunlight as the dominant energy source.

Table 32 compares shape types in four different kinds of landscape disciplines. The classification of landscape components is from the present study. The mental image classes come from Lynch (1960), urban classes are a mixture of city subsystems (see Clay [1973] for more discussion), and the components of art come in part from Klee (1953). This convergence of thought indicates a general principle of the categories of shapes that are adaptive and develop in many different kinds of energy systems. In

Table 32. A comparison of shape classifications in ecology, environmental perception, urban geography, and art.

Landscape Component	Mental Image	Urban Subsystem	Elements in Art
Strip	Path	Highway strip	Line
Zone	Edge	Fringe (urban-rural)	Border
Center	Node	Central business district	Point (foreground)
Background	District	Neighborhood	Background

the example of natural landscape components, shape is an emergent property of the interaction of ecosystem and topographic processes.

Comparison of Energy in Landforms and Ecosystems

Embodied energy, actual energy, and transformation ratios for the ten landforms considered are given in Tables 33 and 34 on an area and volume basis, respectively. Transformation ratios are the same or very nearly the same from either an area or volume view. An exception is the glacier whose great thickness (up to 100 times larger than the other landforms) causes its area-based quality factor to be very low, though the volume-based quality factor is within the range of the other values. The glacier also has the largest actual energy due to its large mass and elevation, which contributes to its relatively low quality factor.

Landform transformation ratios range over 8 orders of magnitude from spoil mound at 10^6 solar Cal/Cal to coral reef at 10^{14} solar Cal/Cal. These values are higher than most other storages (Odum et al. 1978a) that have been calculated. The spoil mound, formed by mechanical energy of strip mining, has lower quality than landforms formed by natural energies over long development times. Of the natural landforms, the two desert examples, sand dune and arroyo, have the smallest transformation ratios due primarily to short development times and to lesser energy inputs. Thus the spoil mound is related to desert conditions as will be noted concerning vegetation development. Three wetland systems—palsa, salt marsh, and seagrass-dominated mud mounds—have similar intermediate quality factors, on the order of 10^9 to 10^{10} solar Cal/Cal, in spite of having very different components and environmental backgrounds.

Table 33. Energy transformation ratios of landforms on an area basis.

Landform	Embodied Energy Input, 10^9 solar Cal/m^2	Actual Energy, Heat Cal/m^2	Transformation Ratio, 10^{10} solar Cal/heat Cal
Floodplain	1,000	1.6	62.5
Coral reef	51,000,000	242.9	21,000
Salt marsh	10.4	5.1	0.2
Glacier	260,000	272,000,000	0.0001
Palsa	9.2	2.5	0.4
Sand dune	30	70.9	0.04
Arroyo	5.1	114.7	0.004
Oyster reef	11,000	5.5	200
Mud mound	75	2.4	3.1
Spoil mound	0.02	20.4	0.0001

Table 34. Energy transformation ratios of landforms on a volume basis.

Landform	Embodied[a] Energy Input, 10^9 solar Cal/m^3	Actual Energy, Heat Cal/m^3	Transformation Ratio, 10^{10} solar Cal/heat Cal
Floodplain	1,000	1.6	62.5
Coral reef	7,300,000	26	28,000
Salt marsh	5.2	2.6	0.2
Glacier	2,000	2,053	0.1
Palsa	2.3	0.5	0.46
Sand dune	5.4	9.6	0.05
Arroyo	0.6	13.6	0.004
Oyster reef	5,500	2.1	262
Mud mound	75	1.9	3.9
Spoil mound	0.007	8.2	0.00009

[a] Embodied energy input divided by depth or thickness of landform, except for spoil mound, which was calculated separately in the footnote to Table 22.

Highest quality landforms are the two reef systems, producer reef (coral reef with algae) at 10^{14} solar Cal/Cal and consumer reef (oyster reef) at 10^{12} along with the floodplain at 10^{12} solar Cal/Cal. All of these systems have complex living structures of reef skeleton or tree roots that contribute directly to the development of the landform. The tropical landforms (coral reef and seagrass mounds) have larger quality factors than the cold climate landforms (glacier and palsa) but these differences are not large.

For additional comparison, energy parameters were calculated for ecosystems of the case study area where possible. Energy in ecosystems was calculated in two ways, from the energy in biomass multiplied by a transformation ratio (Table 35) and, for those systems with available data, from development (succession) time multiplied by embodied energy input as was done with landforms (Table 36). Comparison of embodied energies of landform and ecosystems may indicate which has more control in the landscape.

Comparing biomass-based embodied energy from Table 35 and landform values from Table 33, all natural landforms have much higher embodied energy than corresponding ecosystems, ranging from 10^7 to 10^9 times greater. The spoil mound landform, however, is one order of magnitude less than the biomass value for embodied energy per area. This is probably because the form of the mound is built by machinery with less energy embodied than most natural landforms and because of the high amount of biomass in the spoil mound forest.

Comparisons can be made for three ecosystems by using succession-based embodied energy from Table 36. The significant feature of these values is that they are greater than those based on biomass (Table 35).

Table 35. Biomass-based embodied energy values for ecosystems.

Ecosystem	Ecosystem Biomass, g/m^2	Actual[a] Energy, 10^3 Heat Cal/m^2	Transformation Ratio,[b] solar Cal/Cal	Embodied Energy, 10^6 solar Cal/m^2
Floodplain	23,000[c]	92	2,871[d]	260
Coral reef	846[e]	3.4	---	---
Salt marsh	2,350[f]	9.4	197.6[g]	1.8
Glacier	0	0	---	0
Palsa	3,280[h]	13	239.8[i]	3.1
Sand dune	No data	---	---	---
Arroyo	No data	---	---	---
Oyster reef	269[j]	1.1	4,386[k]	4.8
Mud mound	3,250[l]	13	228.3[m]	2.9
Spoil mound	15,600[n]	62	2,871[d]	180

[a] Biomass x heat content (4.5 Cal/g).
[b] Solar energy input/net production.
[c] Brown et al. 1979.
[d] Natural wood (Odum et al. 1978).
[e] Odum and Odum 1955.

[f] E. P. Odum 1974.

[g] Net production for Sapelo Island, Georgia, salt marsh is 6580 Cal/$m^2 \cdot$yr (Teal 1962) Sunlight from Table 10 is 1.3 x 10^6 solar Cal/$m^2 \cdot$yr. Transformation ratio = (1.3 x 10^6 solar Cal/$m^2 \cdot$yr)/(6580 Cal/$m^2 \cdot$yr) = 197.6 solar Cal/Cal.

[h] Bliss 1975.

[i] Net production for Devon Island peatland is 185.3 g/$m^2 \cdot$yr (Bliss 1975). Energy in this production = (185.3 g/$m^2 \cdot$yr)(4.5 Cal/g) = 833.8 Cal/$m^2 \cdot$yr. Sunlight from Table 14 is 0.2 x 10^6 solar Cal/$m^2 \cdot$yr. Transformation ratio = (0.2 x 10^6 solar Cal/$m^2 \cdot$yr)/(833.8 Cal/$m^2 \cdot$yr) = 239.8 solar Cal/Cal.

[j] Lehman 1974.

[k] Net production for Crystal River oyster reefs is 76 g/$m^2 \cdot$yr (Lehman 1974). Energy in this production = (76 g/$m^2 \cdot$yr)(4.5 Cal/g) = 342 Cal/$m^2 \cdot$yr. Sunlight from Table 20 is 1.5 x 10^6 solar Cal/$m^2 \cdot$yr. Transformation ratio = (1.5 x 10^6 solar Cal/$m^2 \cdot$yr)/(342 Cal/$m^2 \cdot$yr) = 4386 solar Cal/Cal.

[l] Jones 1968.

[m] Net production for South Florida seagrass ecosystem is 2 g C/$m^2 \cdot$day (Jones 1968). Energy in this production = (2 g C/$m^2 \cdot$day)(2 g organic matter/g C)(4.5 Cal/g)(365 day/yr) = 6570 Cal/$m^2 \cdot$yr. Sunlight from Table 21 is 1.5 x 10^6 solar Cal/$m^2 \cdot$yr. Transformation ratio = (1.5 x 10^6 solar Cal/$m^2 \cdot$yr)/(6570 Cal/$m^2 \cdot$yr) = 228.3 solar Cal/Cal.

[n] Biomass of the phosphate forest was calculated using the following equation from Monk et al. (1970) for an oak-hickory forest in Georgia. Log Y = 1.9757 + 2.5371 Log X. Y = mass per tree, g/tree; X = average tree size, dbh in cm. For the phosphate forest the average tree size was 27.5 cm, making mass per tree 424 kg/tree. Using density of trees from Table 26, the total mass of trees = (424 kg/tree)(368 trees/ha)/(10^4 m^2/ha) = 15.6 kg/m^2.

Table 36. Succession-based embodied energy values for ecosystems.

Ecosystem	Succession Time, yr	Embodied Energy Input, 10^9 solar Cal/$m^2 \cdot$yr	Embodied Energy, 10^9 solar Cal/m^2
Floodplain	480[a]	6,800	3,200,000
Sand dune	800[b]	1.2	960
Spoil mound	50[c]	0.07	3.5

[a] Average of data from Fonda (1974), Shelford (1954), and Nixon (1975).
[b] Chadwick and Dalke 1965.
[c] This study.

This suggests that energy is embodied in ecosystem characteristics other than biomass, such as diversity, niche structure, or other emergent properties. Biomass-based ecosystem values depend only on energy in biomass and leave off energy in ecological complexity. The difference between the succession-based value and the biomass-based embodied energy gives a measure for the energy in ecological complexity which is at least 1000 times greater than biomass on an area basis.

Comparing succession-based embodied energy per area with landform values, ecosystems have more energy than landforms. The results of these comparisons are contradictory with those found with biomass values, and it is not clear which ecosystem value is most appropriate for comparison. Do ecosystems control landforms? It is well known that vegetation regulates erosion and deposition of sediments and soils. Also the reef skeletons are directly deposited by the metabolism of the reef organisms. However there is an old school of thought in plant ecology called Physiographic Ecology (Cowles 1901; Braun 1916; Gano 1917), which holds that landforms determine ecosystems together with other factors such as climate. It is suggested by the energy calculations given here that the invisible structure of the ecosystem rather than the physical biomass determines the landscape. More thinking is required concerning interpretation of these numbers. For example, the effect of turnover times of biomass, form, and ecological complexity is one question to be considered.

Energy Effect of Landforms as a Contribution to Human Economies

Like air, land is often taken for granted due to its vast extent and integral importance to human activities. However, land and landform is the platform for human economies and natural ecosystems. As a platform, land is an energy input to the processes and uses that take place upon it. The rate of flow of energy from landforms is the rate at which they are being used up. For an elevated landform this is the rate of erosion and for a depression it is the rate of filling. Before human disturbance, natural vegetation was adapted to control erosion and deposition, as part of the production process shown in Figure 1. In the use of a landscape, however, humans convert natural vegetation to other uses or substitute less mature types of vegetation such as agriculture and lawns. They also disturb the land surface itself in addition to vegetation. These actions tend to increase erosion and deposition and thus increase the rate at which landforms are used. Humans affect the material balance of landforms, which is the geomorphic equivalent of mineral cycling, by drawing down storages built over many years by natural processes. This observation has also been made for human impact on geochemical cycles (Odum 1972). Examples of energy flow for three landforms are given in Table 37. The undisturbed ecosystem uses between 10^2 and 10^5 less landform energy than human land uses.

How this accelerated energy is actually used by human land uses is not entirely clear. The energy is being expended but whether or not it is embodied in the land use is an open question. Some kinds of landform attract development such as river mouths and floodplains, hilltops, and others. When these locations actually generate more economic output than adjacent sites on different landforms then the energy flow from use of the landform probably does get embodied into the land use assets.

As a start at assessing the national impact of human use of landforms, a preliminary calculation was made including the loss of wetlands

Table 37. Comparison of the use of landform energy by three systems, assuming a unit area of 1 km^2 and unit elevation drop of 1 meter.

System Type	Sediment Yield, $t/km^2 \cdot yr$[a]	Actual Energy, Cal/yr[b]
Mature forest, Hubbard Brook	3.3	7.7
Mountain clear-cut, West Virginia	302	700
Construction site, Baltimore, Maryland	49,000	114,000

[a] Bormann and Likens 1979.
[b] Actual energy = (mass)(gravitational acceleration)(height).

and the filling in of reservoirs. These calculations are summarized in Table 38. The sum of these two losses alone is equal to one-third the rate of loss of fossil fuels from U.S. reserves (Leibowitz 1979). Other landforms being consumed include channelization of rivers (loss of meanders), leveling of topography by agriculture, and many others. To what extent these losses are balanced by the construction of farm ponds, dredge and mining spoil mounds, and other human landforms is not known, but it is probably less due to increased erosion rates. The cost of restoring the lost landforms, if it were found necessary to do so, would undoubtedly be high.

Landscape Energy and Aesthetics

The human appreciation of an object for its beauty is its aesthetic value. Although often difficult to evaluate, aesthetic appeal of landscapes is well known. Attraction of visitors to parks is one measurement of this value. Calculations in this dissertation have suggested that different landforms can have widely different embodied energies. They also probably have different aesthetic value. Is the beauty of landscape related to the energy embodied in it? Some of the best known parks are those with very large physical dimensions that are visible or made visible to visitors to the park from observation points. Examples are the Grand Canyon, Niagara Falls, and ocean beaches. Aesthetic value may be proportional to area visible. Human eye perhaps integrates the energy of the large area, with visual appeal related to the total amount of energy that can be seen. Many techniques have been used to measure aesthetic beauty in environmental evaluations (Arthur and Boster 1976), but these "tend to

Table 38. Summary of the national loss of landform energy in wetlands and reservoirs.

Landform Type	Annual Loss, %	Actual Energy Loss, 10^9 Cal/yr	Embodied[a] Energy Loss, 10^{18} solar Cal/yr	Dollar Equivalent, 10^{11} \$/yr
Coastal and inland wetlands	1[b]	4.2	4.2	1.9
Reservoirs	0.2[c]	3.7	3.7	1.7

[a] This was found using an average landform quality factor of 10^9 solar Cal/Cal, see Table 22 for wetland quality factors.

[b] Existing area (Wetzel 1978). This may not represent a complete loss of the form if the wetland is drained only.

[c] Storage capacity (Dendy 1968).

be overly complex, in addition to being highly subjective and value-laden" (Redding 1973). Potential exists for a quantitative theory of landscape aesthetics based on correlation of embodied energy calculations with independent measures of human appreciation such as visitor statistics or questionaires. Odum (1962) discusses the "ecological roots of the aesthetics" and raises the hypothesis that selection for appreciating landscapes may be linked to survival value.

Spoil Mound Succession

Phosphate spoil mound succession, like succession throughout the coastal plain on most fallow agricultural fields (without fire), proceeds from pioneer weeds and old field species through pines to hardwoods. With fire, pines persist without hardwoods (Chapman 1932). Phosphate spoil succession is shown diagramatically in Figure 29. Colonization by weedy forbs begins directly after spoil mounds are deposited. These include *Eupatorium capillifolium*, *Ambrosia artemisifolia*, *Phytolacca rigida*, *Heterotheca subatillaris*, and others. At this early stage, vegetation is very sparse and the landscape is somewhat desertlike in appearance. In fact, vegetation pictures of badlands (Brown 1971) look similar to early stages of spoil mound succession. This was also noted by DeVall and Devane (1949) in an early description of phosphate spoil mound conditions. Grasses such as *Rhynchelytrum repens* and *Paspalum notatum* increase in importance over forbs in the first 5—20 years after mining. Depending on seed source location, trees (*Myrica cerifera*) invade after 5—10 years resulting in savannalike formations. Gradually trees coalesce, forming an open forest canopy with pines dominating, perhaps with scattered hardwoods

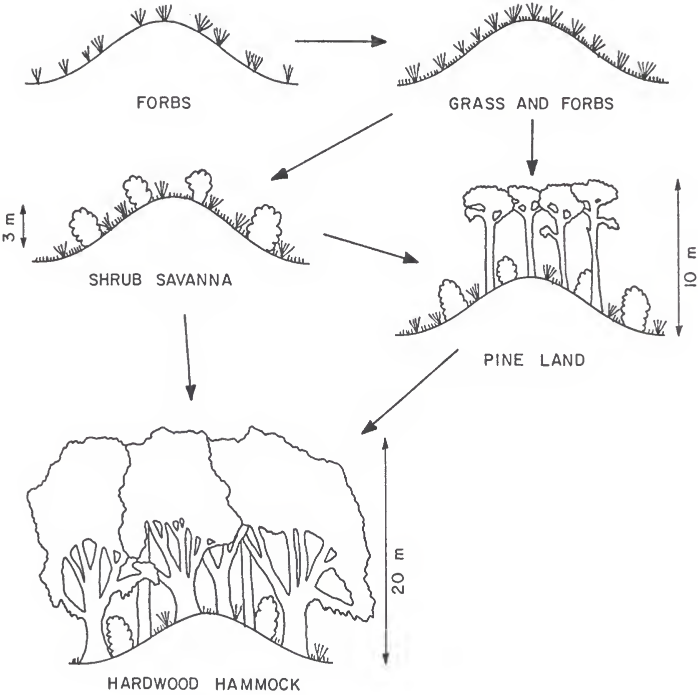


Figure 29. Main stages in phosphate spoil mound succession. Development time is about 50 years to mature hardwood forest.

like wax myrtle, wild cherry, and oak species. As succession proceeds control shifts to hardwoods, which presumably constitute climatic climax conditions.

Details of changes in ecosystem characteristics found in this study are similar to literature reports on other ecosystems. Perino and Risser (1972) and Ewel (1977), using different methods, described similar general patterns of vegetation cover increase through succession. Snedaker (1970) and Ewel (1971) described solar radiation passage through vegetation in tropical succession showing a similar general trend as reported here in terms of optical density. Ewel (1971) and Byer and Weaver (1977) document increases in tree height over successional time.

Several studies have reported aspects of litter and soil organic matter development over succession. Tisdale et al. (1966) describe successional increases in litter depth, and Crocker and Major (1955), Ewel (1968), and Perino and Risser (1972) describe litter weight increases. Likewise Billings (1938), Smith (1940), and Hanks (1972) demonstrate increases in soil organic matter over succession. Billings (1938) also provides data on soil profile development over time in succession.

Maturity of Phosphate Forests

The forest development on 50-year-old sites is perhaps the most striking aspect of spoil mound succession. The existence of forest ecosystems on old spoil mounds demonstrates the potential of natural succession as a reclamation alternative. Determining the maturity of these forests is a prime goal of this study.

Maturity is a common-sense concept used in discussions of age, development, and organization in a variety of contexts. Quantifying maturity of systems is the central problem in succession studies. Margalef (1963, 1968, 1974) suggested the ratio of biomass to productivity as an index of maturity. E. P. Odum (1969) provided general criteria on ecosystem maturity including aspects of community energetics, community structure, life history, nutrient cycling and stability. Whittaker (1966) used the ratio of aboveground biomass to aboveground net productivity (after Margalef) and suggested ratios about 40-50 for the most mature forests in the Great Smoky Mountains (see also Skeen [1974] for an application). Data appropriate for comparison with these indices and criteria are lacking in this study. Instead, comparisons of species compositions based on literature of Florida succession along with comparisons of ecosystem characteristics between the 50-year-old mine sites and an undisturbed hardwood hammock (San Felasco) are used for assessing maturity.

The oldest spoil mound forests studied here are dominated by live oak, Quercus virginiana, with several other hardwoods (water oak, sweetgum, and wild cherry) and a few pines (slash pine). At the Payne Creek site some large pine stumps are found, indicating logging, which might explain the difference in basal area between this site and Christina. Water oak and sweetgum appear to be reproducing, with saplings in the understory, while pine and live oak do not. These forests are similar in composition to the live oak forests described by Laessle and Monk (1961), who reported lack of reproduction by live oak in advanced natural forests. This suggests that live oak is declining at the study sites and transition to another system is taking place. Sellards et al. (1915) described similar forests that they call sandy hammocks and Laessle (1942) described similar stands that he terms xeric hammock.

Detailed studies of Florida succession in the absence of fire generally show a progression from pines to xeric hammocks to climax mesic hammocks (Laessle 1942; Ansley 1952; Quarterman and Keever 1962; Monk 1968; Alexander and Crook 1974; and Veno 1975). The spoil mound forests seem to fit in the transition between xeric and mesic hammock types of this scheme. They are definately post-pine as indicated by the dominance of hardwoods. In terms of species composition the forests might best be described as xeric live oak hammocks. The apparent decline of live oak and the existence and reproduction of more mesophytic hardwoods (sweetgum and water oak) also suggests that transition is occurring to mesic hammock. This is supported by Monk's (1967) classification of the species at the 50-year-old sites as climax pioneers that "invade successional communities and are influential in the conversion to climax."

As a summary of all succession data, Table 39 compares the 50-year-old phosphate forest with San Felasco. The percent difference between the forests is shown in the final column. The San Felasco forest has higher levels for all parameters except percent soil organic matter. The phosphate forest has 23% more organic matter in surface soils compared with San Felasco. A possible explanation may be greater soil respiration at the more mature San Felasco forest drawing down on the storage of organic matter in the soil. Difference for all other ecosystem parameters range from a low of 13% for transmittane of light through the canopy to a high of 69% for number of tree species. Most differences are between 20% and 50% greater development at San Felasco compared with the phosphate forest.

Table 39. Comparison of succession parameters at the phosphate forests with an undisturbed climax forest. Percent difference is defined as the value of the phosphate forest divided by the value of San Felasco Hammock.

Index	Phosphate Forest	San Felasco Hammock	% Difference
Basal area (m^2/ha)	28.5	35.4	19
Density (trees/ha)	368	602	39
Optical density	0.86	1.02	16
Tree height (m)	19.2	25.8	26
Litter depth (cm)	2.5	4.7	47
Litter weight (g/m^2)	1250.4	1594.2	22
Percent organic matter in soil	8.3	6.4	+ 23
Tree species number	5	16	69

A principal difference between the two types of forest is the diversity of tree species. San Felasco has more species and also a more even species abundance distribution. These distributions are shown in Figure 30 in terms of each species contribution to the total basal area. Significant differences between the two forests are more dominance in the phosphate forests by the most common tree species (more than twice as much dominance by live oak compared to magnolia or sweetgum) and the number of rare species (seven species at San Felasco with less than 1% of the total basal area compared to the phosphate forest with no species contributing less than 4%).

Another difference between the phosphate forest and San Felasco hammock is the relationship between basal area and density. Although the basal area of the two forests is somewhat close, the tree density at San Felasco Hammock is almost twice as large as density on the old spoil mounds. Moreover the average tree diameter of the phosphate forest is greater than the average at San Felasco (27.5 cm versus 23.5 cm, respectively). In other words, there are fewer trees in the spoil mound forests but their average size is larger compared with San Felasco Hammock. To examine this observation in more detail, diameter size class distributions of the two forest types were constructed. These were drawn as age class pyramids since size is often used as a surrogate for age in trees. This is another view of hierarchy, in this case in terms of age. Figure 31 shows percent basal area versus size class (31a) and percent of the number of individuals versus size class (31b). The size pyramid for basal area of San Felasco Hammock is almost symmetrical about the middle size class. For the phosphate forest a somewhat bimodal distribution was found with less basal area in the intermediate classes. This could indicate that

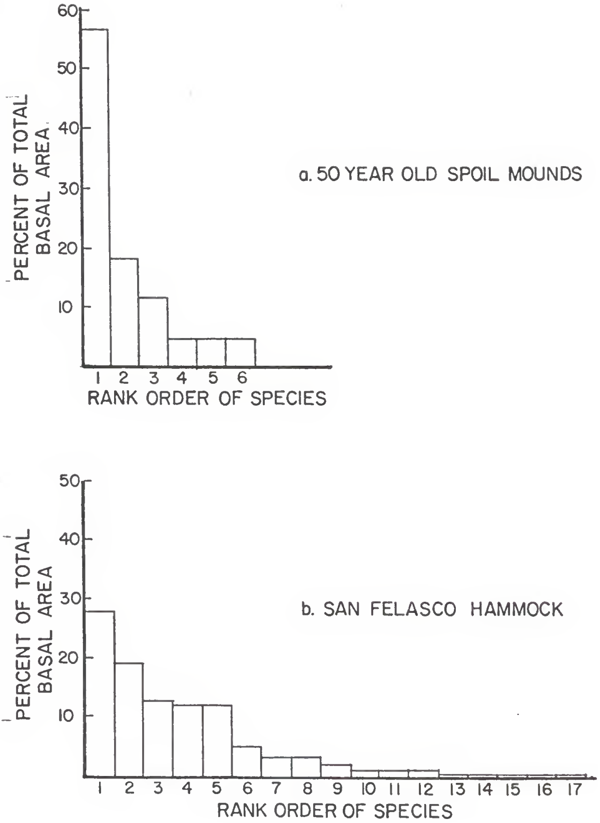


Figure 30. Comparison of basal area distributions by species rank at (a) the 50-year-old spoil mounds and (b) at San Felasco.

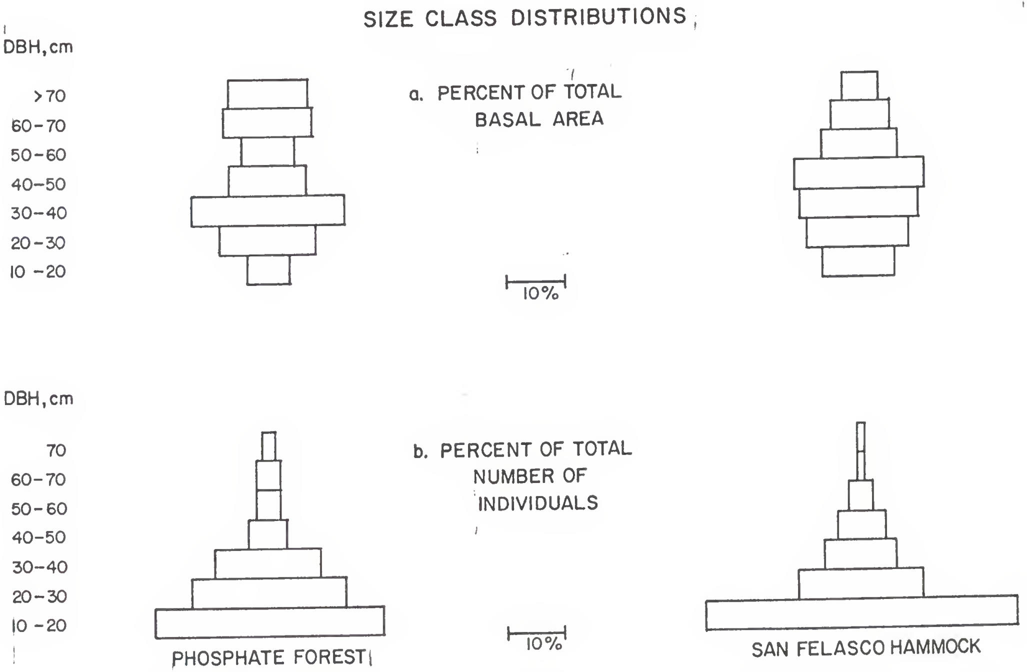


Figure 31. Comparison of size class distributions between the phosphate forest and San Felasco Hammock: (a) percent basal area; (b) percent number of individuals.

selective disturbance occurred in the past, such as logging. The distribution may be smoothed out as the size classes progress through time. The shapes of the size class pyramids of numbers are similar for both forest types. However, numbers in the larger size classes fall off more rapidly for San Felasco than for the phosphate forest. San Felasco Hammock has more trees in the small classes and fewer in the large size classes compared with the phosphate forest.

Table 40 compares the forests in terms of community structure or complexity indices. Again, the percent difference is shown in the final column. Structure is greater at San Felasco for all indices in this case. The Holdrige complexity index gave the greatest difference between the forests at 61%. The three diversity indices give differences of 14% for the Simpson index to 67% for species per 1000. The prediction of 21 species per 1000 at San Felasco is very close to the value of 22 species found by Monk (1960) in more extensive sampling of this forest. Monk (1967) also calculates average Shannon diversities for 162 stands in north-central Florida. The highest average is for mesic, calcareous climax southern mixed hardwoods at 3.07 bits per individual, with a maximum of over 3.60. The value reported in this study for San Felasco is higher than the average for mesic hammocks but lower than the maximum.

Floristic similarity of the forests was calculated with Sorenson's index at 19% with two species in common. This yields a floristic difference of 81%. The similarity index was also calculated using tree species lists from other Florida hardwood hammocks. Included were south Florida tropical hammock (Harper 1921), central Florida sandy hammock (Sellards et al. 1915), southern mixed hardwoods (regional description; Quarterman and Keever 1962), north-central Florida mixed hardwoods (Monk 1965), coastal

Table 40. Comparison of community structure indices at the phosphate forests and San Felasco Hammock. Percent difference is defined as the value of the phosphate forest divided by the value of San Felasco Hammock.

Index	Phosphate Forest	San Felasco Hammock	% Difference
Holdridge Complexity Index	44.4	115.1	61
Simpson Diversity Index	0.75	0.87	14
Shannon Diversity Index	2.16	3.27	34
Species per 1000	7	21	67
Sorenson Similarity Index	--	--	81

live oak hammocks (Laessle and Monk 1961), and north-central Florida mesic hammock (Veno 1976). The species lists are included as Appendix VI with the partial matrix of similarity values given in Table 41. Most values are low, especially for the phosphate forest. This is due to the paucity of species found in the study forests, presumably since sample areas were small. The phosphate forest was found most similar to the central Florida sandy hammock and San Felasco, as expected, was most similar to mixed hardwoods of north-central Florida.

Based on comparison with San Felasco and literature reports, although well developed, the phosphate forest is definately immature and some successional changes toward climax can be expected. The length of time required to reach climax stage is not known. Table 42 provides data on successional time for other forests in the southeastern United States for perspective. The range is from 50 to 300 years. Succession on phosphate spoil probably falls in the lower end of this range. A complicating factor, however, is the composition and quantity of seeding input to the phosphate forests. When the oldest sites were first mined 50 years ago, the surrounding region was much less developed than at present and there were probably many areas of little disturbed vegetation to act as seed source to the mined areas. Under these conditions succession proceeded quickly as indicated by parameters such as the large basal area of phosphate forests. Over time, however, the surrounding vegetation has been replaced with other land uses or at least has been significantly changed. Few, if any, seed sources for climax species exist any longer, which may cause succession on mined land to be arrested to subclimax conditions. Some ecosystem parameters such as cover, litter weight, and basal area may reach climax levels. Other parameters, such as species diversity and

Table 41. Partial similarity matrix comparing species composition of the phosphate forest and San Felasco with other Florida hardwood forests (see text for forest references).

		Phosphate Forest	San Felasco Hammock
Phosphate forest	1	---	0.19
San Felasco Hammock	2	0.19	---
N.C. Florida mesic hammock	3	0.24	0.21
Coastal live oak hammock	4	0.13	0.31
N.C. Florida mixed hardwoods	5	0.09	0.63
Southern mixed hardwoods	6	0.17	0.57
Central Florida sandy hammock	7	0.32	0.60
S. Florida tropical hammock	8	0.10	0.07

Table 42. Age of succession to climax for southeastern United States forests.

Type of Climax	Location	Successional Time, yr	Reference
Oak-Hickory	North Carolina Piedmont	200	Oosting 1942
Mixed hardwoods	S.E. United States region	200–300	Wenger 1968
Cypress	Florida	200	Wharton et al. 1977
Hydric hammock	Florida	100	Wharton et al. 1977
Oak-Hickory	Georgia Piedmont	150	Johnson and Odum 1956
Tropical hammock	South Florida mainland	50[a]	Alexander 1953, 1967; Alexander and Crook 1974
Tropical hammock	Florida Keys	75[a]	Alexander 1953, 1967; Alexander and Crook 1974
Mixed hardwoods	Eastern Mississippi	130	Switzer et al. 1979

[a] Transition ages from pine to tropical hardwoods was given in references. Twenty years were added to account for pine stage.

aspects of size class distributions that represent top levels of population hierarchy may never reach climax development.

Energy Sources and Reclamation

The proportion of the total budget due to reclamation found in this study (0.3%, see Figure 27, page 105) is very similar to the estimate of 0.2% for coal mining given by Ballentine (1976). Although reclamation is not a large portion of the total budget of the phosphate industry according to calculations given here, there is concern and need to make the best use of energy in reclamation. The mining system can be viewed as an order-disorder cycle as shown in Figure 32. Extraction and processing of phosphate pulses ordered land into disordered wastes. Reclamation attempts to restore the wastes back to a more organized state.

A major problem for those involved in reclamation is deciding what to restore. Calculations and measurements in this dissertation showed that spoil mounds may not be wastes but actually valuable storages. Mining topography has energy embodied in it that is wasted if leveled to premining grade as is currently required by law. Not only is landform energy lost in leveling spoil mounds but fuels to drive the machinery are also wasted.

If spoil mounds must be leveled to flat surfaces this may be done more energy effectively by blowing them up with dynamite rather than with large earth-moving machinery. Placing a small charge at the base of a mound would retain some topography but still cut down the angle of the slopes and disperse a large amount of spoil. The cost of this alternative

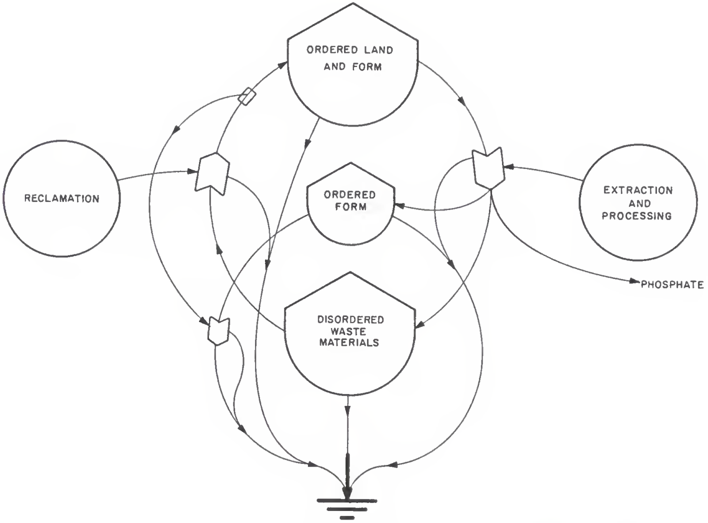


Figure 32. Mining as an order-disorder model. Extraction and processing disperse ordered land while reclamation attempts to restore it. Ordered form results from the extraction process as a by-product and is degraded by reclamation.

is $2053/mound vs $5400/mound if leveled by bulldozers (see footnotes below).

Laws requiring reclamation criteria need to be analyzed on an energy basis. Those laws requiring the leveling of spoil mounds may be doing more harm to the overall system than good. More encouragement for finding ways to use and restore mining wastes through low energy ecological engineering rather than high energy mechanical technology are needed.

Recommendations for Using Succession as Reclamation for Phosphate Spoil Mounds

The problem with natural succession as a reclamation alternative is that it is slow. Techniques for speeding up succession rates would make the alternative more attractive. Subsidizing sensitive aspects of the ecosystem development process that regulate its rate may speed up or "abbreviate" succession (H. T. Odum 1962). As noted by Odum (1962:69), "where succession involves accumulation or consumption of quantities between starting and final climax, the successional stages may be abbreviated by artificial addition or removal of that quantity." Such activities fall in the discipline of ecological engineering (H. T. Odum 1962, 1971; H. T. Odum et al. 1963b), which involves the use of small energies, relative to the natural sources, supplied by man to produce large effects in the resulting ecosystem patterns and processes.

Cost of leveling spoil mounds: to remove rock a charge of 0.5 lbs/yd^3 is suggested (Crimmins et al. 1972). Since spoil material is less dense than rock, assume 1/3 of this charge would be required to blow up a spoil mound. Cost of dynamite is about $35/25 kg (Gregory 1977). Cost to blow up an average spoil mound (4000 yd^3) is then: Dynamite cost = 1/3(0.5 lbs/yd^3)(4000 yd^3/mound)($35/25 kg)(2.2 kg/lb) = $2,053.3/mound. Bulldozer costs is $542.2/400 yd^3 or $1.35/$yd^3$ (Godfrey 1976), making the cost to level a spoil mound = $1.35/$yd^3$(4000 yd^3) = $5,400/mound.

A simulation model of succession was constructed to test certain strategies for the use of succession in reclamation of phosphate spoil mounds. The model developed in this study is compared with other models of upland succession in Table 43. The most detailed model is that of Shugart and West (1977) for Appalachian Mountain hardwoods with 33 species simulated. The phosphate forest succession model is the most aggregated of these models, but all have been usefully applied to practical problems. The model was designed as a management tool to assess the degree to which succession may be able to be accelerated as evaluated by time to climax. The role of shading and germination controls on the rate and transitions of succession were included. Other important features such as soil moisture, seed storages, and mortalities and aspects of mineral cycling could be added to make the model more complete, though the additional complexity might not necessarily add to the utility of the model. Even though highly aggregated, the minimodel of succession used here was validated with comparison of predicted and observed litter values.

The exercise of constructing the model was itself useful in pointing out deficiences in available data on ecosystem development, such as rates of seeding in natural communities and control functions on germination of dominant species. Perhaps research funds should be allocated to investigate these factors for phosphate vegetation.

Two kinds of simulations were studied, seeding and addition of litter. Among the most important aspects of succession are the input of seeds and the role of animals in initiating and maintaining succession. Without seeds or immigration no ecosystem can develop. The advantage of a nearby seed source was observed several times in this study, apparently allowing succession to proceed faster. In several cases, study sites that

Table 43. Comparison of models of upland succession for the southeastern United States.

Location	Model Type	State Variables	Simulations
East Tennessee (Shugart and West 1977)	Computer Subroutines (modification of JABOWA)	Biomass of 33 forest tree taxa and of total forest trees	Long-term forest response to Chestnut blight (plus many other applications)
North Carolina Piedmont (Bledsoe and Van Dyne 1971)	Linear Differential Equations (compartment model)	5 vegetation compartments: grass, forb, pine, oak-hickory, maple, plus soil organic matter and "shade"	Effect of pine harvest and artificial litter removal on succession sequence
North Carolina Piedmont (Johnson 1977)	Linear Differential Equations (compartment model)	Acreage of 9 forest cover types with 3 size classes for each (27 total compartments)	Long-term effects of disturbance and land use practices on regional commercial forest potential
Central Florida (This study)	Non-linear Differential Equations (Energy Circuit Language)	Biomass of 3 vegetation compartments: grass, pine, hardwoods plus litter	Effect of artificial seeding and litter additions on the speed of succession

seemed advanced for their age had nearby seed sources. Model results support this observation in that increased seeding did accelerate succession. Sell (1974) and Gunderson (1976) describe the effects of seeding deficiencies in other ecosystems. The design of mine sites with small scattered areas left untouched as seed sources may then accelerate succession in surrouning mined land. After an area of mined land develops enough to act as a seed source, previously untouched surrounding areas could then be mined, later to be seeded from the ecosystems on old mine land. Whether this plan could be justified on an overall economic basis needs to be analyzed.

The accretion of a litter layer across the soil surface of an ecosystem is another important factor in succession. As Olson (1963:328) states concerning succession, "some biological development may be specifically delayed until litter and soil humus have approached near their steady state values." Perino and Risser (1972) provide an example of litter deficits in terms of biomass in early succession. Litter additions were simulated here under two model structures, with and without a light threshold control on the germination of hardwoods. With light control no advantage to litter addition was found, but without this limiting action succession was accelerated by 30%. This great difference in predictions suggests the model is sensitive to germination control and thus requires further attention. Field germination tests may provide useful information concerning this question. One problem in the use of litter additions is finding an inexpensive analog of true forest litter. The latter is a sensitive substance that both insulates and aerates the soil, has vertical stratification of characteristics, and has high embodied energy (in the standard simulation run, Figure 25a, litter took 50 years to reach steady state). Wood chips, hay, and other kinds of mulch may be poor substitutes for natural litter. Because of this, seeding strategies may be a more efficient approach to accelerating phosphate succession.

Succession can be accelerated even faster if some idea of the successional sequence is known. The strategy consists of shortening the length of each stage in succession by seeding advance stages at each step. In other words, suppose a transition between two successional stages takes 10 years with natural seeding rates. It may be possible to cut the transition time greatly by increasing the seeding rate of the advanced stage after allowing the previous stage a minimal development of say 5 years. This does not mean jump a stage, but rather accelerate it. This may be necessary since each successional stage "prepares" or conditions the site for the next stage. To illustrate this principle, an example of how it might be applied to phosphate spoil mound restoration is given below.

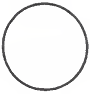
Previous work has identified the main stages of succession on phosphate spoil mounds (Figure 29, page 130) along with transition times. The general sequence is for forbs and grasses to colonize the mounds within 1 year. Scattered trees first appear after 10 years and within 20 years tree canopies close forming initial forest structure. Near-climax hardwood hammock conditions can be reached after 50 years. The accelerated succession principle uses this known sequence to speed succession. A possible restoration schedule might be as follows:

1. Plant weed seeds such as dogfennel the first few years to develop initial plant cover, which generates litter and soil organic matter.

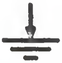
2. Plant early successional shrub and tree seeds like wax myrtle, willows, elderberry, and other species after 3 years. These are fast growing and should quickly develop a shrub woodland.
3. Finally, plant seeds of climax species after about 10 years to grow up in the shade of the shrub woodland. Growth will be slow and some clearing or herbiciding of shrubs may be necessary to help climax seedlings emerge. Near climax conditions could be reached in 25 years perhaps, cutting the natural succession time in half.

The simulations of succession with added seeds support the idea of seral subsidy suggested above.

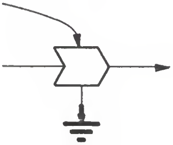
APPENDIX I
KEY TO THE SYMBOLS IN THE ENERGY CIRCUIT LANGUAGE



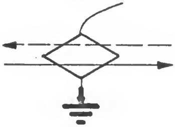
Energy source (forcing function), source of external cause.



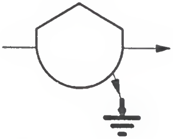
Heat sink, outflow of used energy



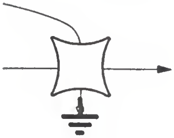
Energy interaction, one type of energy amplifies energy of a different quality (usually a multiplier)



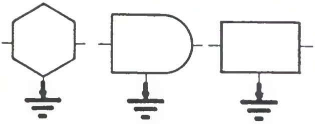
Economic transaction and price function



Storage (state variables)



On-off switch (digital actions)



Group symbols (1) autocatalytic self-maintenance units, (2) production units, and (3) general purpose box for miscellaneous subsystems.

APPENDIX II
CASE STUDY DATA TABLES

Appendix II-A. Floodplain case study data table.

Parameter	Value	Reference
Solar Insulation	1.0×10^6 Solar Cal/$m^2 \cdot yr$	Odum et al. 1978
Absolute Temperature, T	281°K	NOAA 1974
Precipitation	78 cm/yr	NOAA 1974
TDS of Precipitation	14 ppm	Odum et al. 1978
TDS of Receiving Water	100 ppm	Assumed
Wind Velocity, V	478.3 cm/s	NOAA 1974
Mass of Organic Matter Inflow, M_o	336 $g/m^2 \cdot yr$	*
Runoff	25.4 cm/yr	Odum et al. 1978
Runoff Head, H_r	100 cm	Assumed
Flood Head, H_f	7625 cm	Say and Janssen 1976
Duration of Flood, F	2.16×10^4 s/yr	†
Flood Discharge, D	8.5×10^7 cm^3/s	Corps of Engineers 1976
Area of Floodplain, A	6.96×10^7 m^2	Corps of Engineers 1976
Landform Density, D	1.36 g/cm^3	Same as Arroyo
Landform Volume, V	6.96×10^7 m^3	§
Concentration Area, C	23 m^2/m^2	**
Development Time, D_T	10,000 yr	Time since last glaciation in southeast Michigan, assumed

*Organic inflows in floodwaters: Wolman and Leopold (1970) give an average deposition rate in major floods of about 0.1 foot (3.1 cm). Assuming a recurrence interval of 20 years, the annual rate of deposition is 3.1 cm/20 years = 0.16 cm/yr. In terms of mass of sediments this is $(0.16\ cm/yr)(10^4\ cm^2/m^2)(1.4\ g/cm^3) = 2.2 \times 10^3\ g/yr$. Assume an organic content of 15% (Brown et al. 1979). $M_o = 336\ g/m^2 \cdot yr$.

†F = duration of flood per year, assumed $(5\ days/flood)(flood/20\ yr)(8.64 \times 10^4\ s/day) = 2.16 \times 10^4\ s/yr$.

§Volume (rectangle) = area x depth. Area = $6.96 \times 10^7\ m^2$ (USGS 1979). Depth = 1 m (assumed). Volume = $6.96 \times 10^7\ m^3$.

**Floodplain concentration area using Huron River data from Table 5: Concentration area = (watershed area)/(floodplain area) = $(2.3 \times 10^9\ m^2)/(1.0 \times 10^8\ m^2) = 23\ m^2/m^2$.

Appendix II-B. Coral reef case study data table.

Parameter	Value	Reference
Solar Insolation	1.5×10^6 Solar Cal/$m^2 \cdot yr$	Ruttenberg 1979
Wind Velocity, V	378.8 cm/s	Ruttenberg 1979
Tidal Head, H_T	40 cm	Ruttenberg 1979
Number of Tides/Year, n	717	Ruttenberg 1979
Mass of Organic Matter Inflow, M_O	730 g/$m^2 \cdot yr$	Odum and Odum 1955
Wave Head, H_W	30.5 cm	Ruttenberg 1979
Width of Area Affected, W	30.5 m	Assumed
Landform Volume, V	3.27×10^6 m^3	*
Landform Density, D	3.17 g/cm^3	Statham 1977
Concentration Area, C	588 m^2/m^2	†
Development Time, D_T	700 yrs	§

*Volume (1/2 ellipsoid) = 4/3 π abc; a = length = 2400 ft = 731.5 m, b = width = 500 ft = 152.4 m, c = height = 23 ft = 7.0 m (all from Shinn 1963), V = 3.27×10^6 m^3

†Coral reef concentration area is given by Smith (1978) at 0.17% of global ocean or 588 m^2/m^2.

§Development time for the 7-m-thick reef considered, using a growth rate of 1 cm/yr from Table 7 is Development time = (700 cm)/(1 cm/yr) = 700 years.

Appendix II-C. Salt marsh case study data table.

Parameter	Value	Reference
Solar Insolation	1.3×10^6 Solar Cal/m^2·yr	Odum et al. 1978
Absolute Temperature, T	292°K	NOAA 1974
Precipitation	124 cm/yr	NOAA 1974
TDS of Precipitation	8 ppm	Odum et al. 1978
TDS of Receiving Waters	28,000 ppm	Assumed
Wind Velocity, V	375.5 cm/s	NOAA 1974
Tidal Head, H_T	2.2 m	Odum et al. 1978
Number of Tides/Year, n	700	Assumed
Runoff	20.3 cm/yr	Odum et al. 1978
Runoff Head, H_R	100 cm	Teal 1962
Landform Density, D	0.2 g/cm^3	McCaffrey and Thompson 1980
Landform Volume, V	2.28×10^7 m^3	*
Concentration of Area, C	2 m^2/m^2	†
Development Time, D_T	300 yrs	§

*Volume (rectangle) = area x height. Area = 11.4 km^2 = 1.14×10^7 m^2 (Bahr 1976); Height = 2 m (Teal 1962); Volume = 2.28×10^7 m^3.

†Concentration area of Sapelo Island salt marsh was assumed to be 2 m^2/m^2, see map in Bahr (1976).

§Development time taken from Table 9 was 300 yrs.

Appendix II-D. Glacier case study data table.

Parameter	Value	Reference
Solar Insolation	0.6×10^6 Solar Cal/$m^2 \cdot yr$	Odum et al. 1978
Absolute Temperature, T	277°K	NOAA 1974
Precipitation	203 cm/yr	NOAA 1974
TDS of Precipitation	18 ppm	Assumed
TDS of Receiving Waters	100 ppm	Assumed
Wind Velocity, V	536.4 cm/s	NOAA 1974
Uplift Rate	0.5 cm/yr	Schumm 1963
Landform Density, D	0.88 g/cm^3	Lachapelle 1965
Landform Volume, V	5.7×10^8 m^3	Table 11
Concentration of Area, C	34 m^2/m^2	*
Development Time, D_T	3×10^4 yrs	Porter 1971

*Glacier concentration area is given by Flint (1957) at about 10% of world land area in glaciers, which divided into total area of the earth is $(5.1 \times 10^{14}\ m^2)/(1.5 \times 10^{13}\ m^2) = 34\ m^2/m^2$.

Appendix II-E. Palsa mound case study data table.

Parameter	Value	Reference
Solar Insolation	0.2×10^6 Solar $Cal/m^2 \cdot yr$	Bliss 1975
Absolute Temperature, T	279°K	Bliss 1975
Precipitation	28.4 cm/yr	Bliss 1975
TDS of Precipitation	10 ppm	Assumed
TDS of Receiving Waters	100 ppm	Assumed
Wind Velocity, V	210 cm/s	Bliss 1975
Runoff	10 cm/yr	Assumed
Runoff Head, H_R	200 cm	Kershaw and Gill 1979
Temperature Change, T	15°C	Assumed
Heat Capacity of Soil Substrate, H_C	4.4×10^{-4} $Cal/cm^3 \cdot °C$	Kelley and Weaver 1969
Volume Affected, V_F	10^6 cm^3/m^2	*
Length of Cycle, t	1 day	Assumed
Number of Cycles/Year, n	150	Assumed
Landform Density, D	0.1 g/cm^3	Zoltai and Tarnocai 1971
Landform Volume, V	1×10^4 m^3	†
Concentration of Area, C	1 m^2/m^2	§
Development Time, D_T	4000 yrs	Table 13

*Volume = assumed depth of freeze and thaw is 100 cm, thus $V = (100\ cm)(10^4\ cm^2/m^2) = 10^6\ cm^3/m^2$.

†Volume (1/2 ellipsoid) = $4/3\ \pi\ abc$; a = length = 40 m, b = width = 15 m, c = height = 4 m, (all from Kershaw and Gill 1979).

§Palsa concentration area is their surface area only since most water for the ice core comes from below.

Appendix II-F. Sand dune case study data table.

Parameter	Value	Reference
Solar Insolation	1.2×10^6 Solar Cal/$m^2 \cdot yr$	Odum et al. 1978
Absolute Temperature, T	295°K	Oklahoma Biol. Survey n.d.
Precipitation	20.3 cm/yr	Oklahoma Biol. Survey n.d.
Wind Velocity, V	670 cm/s	McKee and Douglas 1971
Runoff	2.54 cm/yr	Odum et al. 1979
Runoff Head, H_R	320 cm	McKee 1966
Sand Flux	60 cm/yr	Footnote to Table 16
Landform Density, D	1.5 g/cm^3	Brady 1974
Landform Volume, V	4.05×10^5 m^3	†
Concentration of Area, C	10 m^2/m^2	§
Development Time, D_T	9 yrs	Table 15

†Volume (1/2 ellipsoid) = 4/3 π abc; a = length = 420 ft = 128 m, b = width = 450 ft = 137.2 m, c = height = 18 ft = 5.5 m (all from McKee 1966), Volume = 4.05×10^5 m^3.

§Sand dune concentration area is given by Egler (1977) at 10% of deserts covered with dunes or 10 m^2/m^2.

Appendix II-G. Arroyo case study data table.

Parameter	Value	Reference
Solar Insolation	1.2×10^6 Solar Cal/m$^2\cdot$yr	Odum et al. 1978
Absolute Temperature, T	295°K	NOAA 1974
Precipitation	20.65 cm/yr	NOAA 1974
TDS of Precipitation	12 ppm	Odum et al. 1978
TDS of Receiving Water	100 ppm	Assumed
Wind Velocity, V	397.8 cm/s	NOAA 1974
Storm Kinetic Energy	1×10^4 Cal/m$^2\cdot$storm	Odum et al. 1978; Odum 1978b
Number of Storms/Yr, n	3	Assumed
Landform Density, D	1.36 g/cm^3	Miller and Wendorf 1958
Landform Volume, V	1.21×10^8 m^3	*
Concentration of Area, C	35.7 m^2/m^2	†
Development Time, D_T	43 yrs	Table 17

*Volume (rectangle) = abc; a = length = 150 miles = 1.64×10^5 m, b = width = 285 ft = 86.9 m, c = depth = 28 ft = 8.5 m (all from Leopold et al. 1964), volume = 1.21×10^8 m^3.

†Arroyo concentration area = (watershed area)/(arroyo area) = (7.5×10^8 m^2)/(2.1×10^7 m^2) (calculated from Leopold et al. 1964) = 35.7 m^2/m^2.

Appendix II-H. Oyster reef case study data table.

Parameter	Value	Reference
Solar Insolation	1.5×10^6 Solar Cal/$m^2 \cdot yr$	Kemp 1977
Absolute Temperature, T	293°K	Kemp 1977
Runoff	6.1×10^7 $cm^3/m^2 \cdot yr$	*
TDS of Runoff	120 ppm	Kemp 1977
TDS of Receiving Water	24,000 ppm	Kemp 1977
Wind Velocity, V	433 cm/s	Kemp 1977
Tidal Head, H_T	70.1 cm	Kemp 1977
Number of tides/Yr, n	705	Kemp 1977
Mass of Organic Matter Inflow, M_O	2.5×10^4 $g/m^2 \cdot yr$	Lehman 1974
Landform Density, D	0.89 g/cm^3	May 1971
Landform Volume, V	2.09×10^5 m^3	†
Concentration of Area, C	33 m^2/m^2	§
Development Time, D_T	766 yrs	**

*M = mass of runoff per year; total runoff = 48.5×10^9 m^3/yr (Kemp 1977); Area of bay = 7.98×10^8 m^2; runoff = $(48.5 \times 10^9\ m^3/yr)/(7.98 \times 10^8\ m^2) = 60.7$ $m^3/m^2 \cdot yr$, or 6.1×10^7 $cm^3/m^2 \cdot yr$.

†Volume (1/2 ellipsoid) = 4/3 π abc; a = length = 500 m, b = width = 50 m, c = height = 2 m (assumed) (a and b from Lehman 1974), Volume = 2.09×10^5 m^3.

§Oyster reef concentration area is given by Lehman (1974) at 3% of total bay area or 33 m^2/m^2.

**Development time is calculated below with data from May (1971) using the 2-m thickness of Crystal River reef. Development time = [(920 yr)(2 m)]/[(8 ft)(0.3 m/ft)] = 766 years.

Appendix II-I. Marine mud mound case study data table.

Parameter	Value	Reference
Solar Insolation	1.5×10^6 Solar Cal/$m^2 \cdot yr$	Ruttenberg 1979
Absolute Temperature, T	295 °K	Scholl 1966
Runoff	2.0×10^6 $cm^3/m^2 \cdot yr$	*
TDS of Runoff	120 ppm	Assumed
TDS of Receiving Water	35,000 ppm	Scholl 1966
Wind Velocity, V	378.8 cm/s	Ruttenberg 1979
Tidal Head, H_T	24 cm	Scholl 1966
Number of tides/Yr, n	717	Ruttenberg 1979
Landform Density, D	1.58 g/cm^3	Scholl 1966
Landform Volume, V	1.85×10^7 m^3	†
Concentration of Area, C	4.4 m^2/m^2	§
Development Time, D_T	2000 yrs	Enos and Perkins 1979

*Assume 1/4 of the runoff from the Everglades watershed enters Florida Bay. Average annual runoff over the 900 square mile area of the Everglades is 7.5 inches (Parker 1974). On a volume basis this is Total runoff = (900 sq mi)(2.59×10^6 m^2/sq mi)(10^4 cm^2/m^2) (7.5 in./yr)(2.54 cm/in.) = 4.4×10^{15} cm^3/yr. This runoff volume mixes over the area of Florida Bay making (2.18×10^9 m^2 from Scholl 1966) runoff on area basis: Runoff per m^2 = (4.4×10^{15} cm^3/yr)/(2.2×10^9 m^2) = 2.0×10^6 $cm^3/m^2 \cdot yr$. Mass of runoff = (2.0×10^6 $cm^3/m^2 \cdot yr$)(1 g/cm^3) = 2.0×10^6 $g/m^2 \cdot yr$.

†Volume (1/2 ellipsoid) = 4/3 π abc; a = length = 7000 m, b = width = 630 m, c = height = 1 m (all from Enos and Perkins 1979), Volume = 1.85×10^7 m^3.

§Marine mud mound concentration area is given by Scholl (1966) at 23% of area of Florida Bay, or 4.4 m^2/m^2.

Appendix II-J. Spoil mound case study data table.

Parameter	Value	Reference
Solar Insolation	1.5×10^6 Solar Cal/$m^2 \cdot yr$	McCuller 1975
Absolute Temperature, T	293°K	NOAA 1974
Precipitation	127 cm/yr	McCuller 1975
TDS of Precipitation	8 ppm	Odum et al. 1978
TDS of Receiving Water	100 ppm	Assumed
Wind Velocity, V	366.5 cm/s	McCuller 1975
Runoff	25.4 cm/yr	Odum et al. 1978
Runoff Head, H_R	250 cm	T. Oxford, pers. comm.
Dragline	5.0×10^6 Solar Cal/yd^3	Footnote to Table 22
Landform Density, D	1.4 g/cm^3	Assumed
Landform Volume, V	3000 m^3	Footnote to Table 22

APPENDIX III
SUCCESSION MODEL COEFFICIENT CALCULATIONS (see Figure 20)

J = incident sunlight = 1,460,000 $Cal/m^2 \cdot yr$;
R = remaining sunlight = 365,000 $Cal/m^2 \cdot yr$;
Q_1 = hardwood biomass = 15,700 g/m^2 (Lugo et al. 1978);
Q_2 = pine biomass = 9,000 g/m^2 (Wiegert and Monk 1972);
Q_3 = grass biomass = 500 g/m^2 (average value from Odum 1960; Golley 1965);
Q_4 = litter mass = 1184 g/m^2 (model was scaled with this value as characteristic of later stages of succession, see Table 27);
K_1Q_1R = sunlight used by hardwoods = 1,095,000 $Cal/m^2 \cdot yr$;
K_1 = (1,095,000 $Cal/m^2 \cdot yr$)/[(15,700 g/m^2)(365,000 $Cal/m^2 \cdot yr$)] = 1.91×10^{-4};
L_1Q_2R = sunlight used by pines = 1,095,000 $Cal/m^2 \cdot yr$;
L_1 = (1,095,000 $Cal/m^2 \cdot yr$)/[(9,000 g/m^2)(365,000 $Cal/m^2 \cdot yr$)] = 3.33×10^{-4};
M_1Q_3R = sunlight used by grasses = 1,095,000 $Cal/m^2 \cdot yr$;
M_1 = (1,095,000 $Cal/m^2 \cdot yr$)/[(500 g/m^2)(365,000 $Cal/m^2 \cdot yr$)] = 6×10^{-3};
K_2Q_1R = hardwood gross primary production calculated with data from Lugo et al. (1978);
Gross production = (17.5 $g/m^2 \cdot day$)(270 days/yr; 9-month growing season) = 4725 $g/m^2 \cdot yr$;
K_2 = (4725 $g/m^2 \cdot yr$)/[(15,700 g/m^2)(365,000 $Cal/m^2 \cdot yr$)] = 8.25×10^{-7};
L_2Q_2R = pine gross primary production calculated with an average from Bayley et al. (1974) and Dugger et al. (1975);
Gross production = (6.75 g $C/m^2 \cdot day$)(2 g organic matter/g C)(270 day/yr; 9-month growing season) = 3645 $g/m^2 \cdot yr$;
L_2 = (3645 $g/m^2 \cdot yr$)/[(9000 g/m^2)(365,000 $Cal/m^2 \cdot yr$)] = 1.11×10^{-6};
M_2Q_3R = grass gross primary production calculated from data from Golley (1965);
Gross production = 794 $g/m^2 \cdot yr$;
M_2 = (794 $g/m^2 \cdot yr$)/[(500 g/m^2)(365,000 $Cal/m^2 \cdot yr$) = 4.35×10^{-6};
K_3Q_1 = hardwood respiration calculated by difference as gross production - litter fall, 3656 $g/m^2 \cdot yr$;
K_3 = (3656 $g/m^2 \cdot yr$)/(15,700 g/m^2) = 0.233;
L_3Q_2 = pine respiration calculated by difference as gross production - litter fall, 3119 $g/m^2 \cdot yr$;
L_3 = (3119 $g/m^2 \cdot yr$)/(9000 g/m^2) = 0.347;
M_3Q_3 = grass respiration calculated by difference as gross production - litter fall, 487 $g/m^2 \cdot yr$;
M_3 = (487 $g/m^2 \cdot yr$)/(500 g/m^2) = 0.974;
N_1Q_4 = decomposition rate = total litter fall as steady state = 1069 $g/m^2 \cdot yr$;
N_1 = (1069 $g/m^2 \cdot yr$)/(1184 g/m^2) = 0.903;
K_4Q_4 = hardwood litter fall from Lugo et al. (1978) = 1069 $g/m^2 \cdot yr$;
K_4 = (1069 $g/m^2 \cdot yr$)/(15,700 g/m^2) = 0.068;
L_4Q_2 = pine litter fall from Wiegert and Monk (1972) = 526 $g/m^2 \cdot yr$;
L_4 = (526 $g/m^2 \cdot yr$)/(9000 g/m^2) = 0.058;
M_4Q_4 = grass litter fall average from Odum (1960) and Golley (1965) = 307 $g/m^2 \cdot yr$;
M_4 = (307 $g/m^2 \cdot yr$)/(500 g/m^2) = 0.614;
S_1 = hardwood seed germination, assumed = 0.1 $g/m^2 \cdot yr$;
S_2 = pine seed germination, assumed = 0.1 $g/m^2 \cdot yr$;
S_3 = grass seed germination, assumed 1 $g/m^2 \cdot yr$.

APPENDIX III
SUCCESSION SIMULATION PROGRAM

```
1 CLEAR (500)
3 INPUT "WHAT IS THE LENGTH OF TIME TO RUN";T0
5 GOSUB 2000
6 INPUT "OUTPUT TO CRT(0) OR PRINTER(1)";F2
7 INPUT "WHAT IS THE DESCRIPTION OF RUN";B$
8 IF F2=0 THEN PLOT 12
9 IF F2=1 THEN PLOT 4 : PRINT B$
10 J=1.46E6
12 T1=575
13 T2=250
14 T3=400000
15 N1=.9029
20 K1=1.91E-4
30 K2=8.25E-7
40 K3=.233
50 K4=.068
60 L1=3.33E-4
62 L2=1.11E-6
64 L3=.347
66 L4=.058
72 M1=6E-3
74 M2=4.35E-6
76 M3=.974
78 M4=.614
80 S1=0
83 S2=0
86 S3=1
88 E1=0
90 E2=0
92 E3=0
94 Q1=0
95 Q2=0
96 Q3=0
97 Q4=0
98 INPUT "WHAT IS DT";DT
100 T=T+DT
110 R1=J/(1+K1*Q1)
115 R2=R1/(1+L1*Q2)
120 R3=R2/(1+M1*Q3)
125 P1=K2*Q1*R1
130 P2=L2*Q2*R2
135 P3=M2*Q3*R3
160 IF Q4>T1 GOTO 1100
170 Q1=Q1+DT*(P1-(K3*Q1)-(K4*Q1))+S1
175 IF Q4>T2 GOTO 1120
```

```
185 Q2=Q2+DT*(P2-(L3*Q2)-(L4*Q2))+S2
187 IF T>0 GOTO 6000
190 Q3=Q3+DT*(P3-(M3*Q3)-(M4*Q3))+S3
195 Q4=Q4+DT*((K4*Q1+L4*Q2+M4*Q3)-(N1*Q4))
200 IF F2=0 THEN 300
210 Q=Q1/200 : F=1 : GOSUB 5000
220 Q=Q2/200 : F=2 : GOSUB 5000
230 Q=Q3/50 : F=3 : GOSUB 5000
240 Q=Q4/100 : F=4 : GOSUB 5000
270 F1=F1+DT : IF ~~F1=1~~ THEN PRINT P$ : F1=0
280 P$=A$           F1=>1
290 POKE 40838,10
300 PLOT 29 : PLOT 18
310 PLOT 2
320 PLOT T : PLOT Q1/200
330 PLOT 255
340 PLOT 29 : PLOT 20
350 PLOT 2
360 PLOT T : PLOT Q2/200
370 PLOT 255
380 PLOT 29 : PLOT 17
390 PLOT 2
400 PLOT T : PLOT Q3/50
410 PLOT 255
420 PLOT 29 : PLOT 21
430 PLOT 2
440 PLOT T : PLOT Q4/100
450 PLOT 255
600 IF T<T0 THEN 100
700 PRINT "FINAL VALUES"
710 PRINT "Q1=";Q1,"Q2=";Q2,"Q3=";Q3,"Q4=";Q4
899 IF F2=1 THEN PLOT 5
900 END
1100 IF R2>T3 GOTO 170
1101 S1=.1
1103 IF Z1=1 GOTO 170
1105 Q1=Q1+E1
1107 Z1=1
1110 GOTO 170
1120 S2=.1
1123 IF Z2=1 GOTO 185
1125 Q2=Q2+E2
1130 Z2=1
1135 GOTO 185
2000 REM
2010 FOR I=1 TO 8 : A$=A$+"         :" : NEXT
2020 FOR I=1 TO 8 : A1$=A1$+"---------!" : NEXT
2030 F$="1234567890"
2040 RETURN
5000 REM  PLOTTING ROUTINE FOR PRINTER
5010 Q=INT(Q)
5020 IF Q<2 THEN Q=2
5030 IF Q>79 THEN Q=79
5040 Z$=MID$(F$,F,1)
```

```
5050 P$=LEFT$(P$,Q-1)+Z$+RIGHT$(P$,80-Q)
5060 RETURN
6000 IF A=1 GOTO 190
6005 Q3=Q3+E3
6010 A=1
6015 GOTO 190
_

PLOT5
```

APPENDIX V
CALCULATIONS FOR PHOSPHATE MINING AND FERTILIZER OPERATION MODEL (see Fig. 27)

(a) Embodied energy costs of purchased inputs.

Mine inputs (Greene 1978): Electricity = 112 x 10^6 KWH/yr; embodied energy = (112 x 10^6 KWH/yr)(860.5 Cal/KWH)(8000 solar Cal/Cal) = 7.7 x 10^{14} solar Cal/yr. Labor = 6.5 x 10^6 \$/yr; embodied energy = (6.5 x 10^6 \$/yr)(2.2 x 10^7 solar Cal/\$) = 1.4 x 10^{14} solar Cal/yr. Fossil fuel (oil and gas) = 1.7 x 10^6 Gal/yr; embodied energy = (1.7 x 10^6 Gal/yr)(3.5 x 10^4 Cal/Gal) (3100 solar Cal/Cal) = 1.8 x 10^{14}d solar Cal/yr. Capital investment = 8 x 10^7 \$/20 yr = 4 x 10^6 \$/yr; embodied energy = (4 x 10^6 \$/yr)(2.2 x 10^7 solar Cal/\$) = 0.9 x 10^{14} solar Cal/yr. Total mine inputs (x 10^{14} solar Cal/yr): Electricity, 7.7; Labor, 1.4; Fossil fuel, 1.8; Capital investment, 0.9; Total = 11.8.

Fertilizer plant inputs (Phillips 1975): Sulfuric acid = 2.75 tons acid/ton fertilizer; embodied energy = (2.75 tons acid/ton)(1.2 x 10^6 tons/yr)(\$35/ton acid)(2.2 x 10^7 solar Cal/\$) = 2.5 10^{15} solar Cal/yr. Electricity = 3.3 KWH/ton; embodied energy = (3.3 KWH/ton)(1.2 x 10^6 tons/yr)(860.5 Cal/KWH) (8000 solar Cal/Cal) = 2.7 x 10^{13} solar Cal/yr. Labor = 0.51 man-hours/ton; embodied energy = (0.51 man-hours/ton)(1.2 x 10^6 tons/yr)(\$5/man-hour)(2.2 x 10^7 solar Cal/\$) = 6.7 x 10^{13} solar Cal/yr. Maintenance = \$11.47/ton; embodied energy = (\$11.47/ton)(1.2 x 10^6 tons/yr)(2.2 x 10^7 solar Cal/\$) = 3.0 x 10^{14} solar Cal/yr. Taxes, interest, overhead = \$13.48/ton; embodied energy = (\$13.48/ton)(1.2 x 10^6 tons/yr)(2.2 x 10^7 solar Cal/\$) = 3.6 x 10^{14} solar Cal/yr. Capital investment = 40.87 x 10^6 \$/15 yr = 2.73 x 10^6 \$/yr; embodied energy = (2.73 x 10^6 \$/yr)(2.2 x 10^7 solr Cal/\$) = 6.0 x 10^{13} solar Cal/yr. Total fertilizer plant inputs (x 10^{15} solar Cal/yr): Sulfuric acid, 2.50; Electricity, 0.03; Labor, 0.07; Maintenance, 0.30; Taxes, interest, overhead, 0.40; Capital investment, 0.06; Total = 3.36.

Total industry purchased inputs = Mine input + Fertilizer plant input = 1.2 x 10^{15} solar Cal/yr + 3.4 x 10^{15} solar Cal/yr = 4.6 x 10^{15} solar Cal/yr.

(b) Embodied energy in phosphate fertilizer sold to market. Phosphoric acid fertilizer is 19% phosphoric acid by weight, the remaining portions being filler. The molecular weight of phosphoric acid, H_3PO_4, is 98 g/mole of which 32% is phosphorus. The weight of phosphorus in fertilizer is (1 ton) (10^6 g/ton)(0.19)(0.32) = 6.08 x 10^4 g P/ton fertilizer. Using the embodied energy per gram of phosphorus, 7.63 x 10^5 solar Cal/g, from Odum and Odum (1980) and the annual fertilizer production, the total embodied flow to market is $(1.2 \times 10^6$ tons/yr$)(6.1 \times 10^4$ g P/ton$)(7.63 \times 10^5$ solar Cal/g$) = 5.58 \times 10^{16}$ solar Cal/yr.

(c) Natural energy input. Embodied energy flow = $(2.1 \times 10^6$ solar Cal/m$^2 \cdot$yr; see Table 22)(400 acre/mine)(4047 m^2/acre) = 3.4×10^{12} solar Cal/yr.

(d) Embodied energy input to reclamation

Clay ponds. 2500 acres of clay ponds are produced each year in the central Florida phosphate district (Anonymous 1974). Dividing by the average annual production of 34,000,000 tons (Phosphate Land Reclamation Study Commission 1978) yields (2500 acres/yr)/(34,000,000 tons/yr) = 0.0001 acres/ton rock. Dollar cost of clay pond reclamation is $1,313/acre (Phosphate Land Reclamation Study Commission 1978), making the embodied energy cost per ton (0.0001 acres/ton) ($1313/acre)$(2.2 \times 10^7$ solar Cal/$) = 2.9×10^6 solar Cal/ton, or $(2.9 \times 10^6$ solar Cal/ton rock)(3.31 ton rock/ton fertilizer) = 9.6×10^6 solar Cal/ton fertilizer.

Overburden spoil. An average mine operates on 400 acre/yr (EPA 1978) and extracts 5×10^6 tons rock/yr (Greene 1978). Acres to be reclaimed per ton of product, assuming onequarter of the area in spoil mounds, is (0.25)(400 acres/yr)$(5 \times 10^6$ tons/yr) = 0.00002 acres/ton. Dollar costs of spoil reclamation range from a low of $300/acre (Wang et al. 1974) to $1587.5/acre (Phosphate Land Reclamation Study Commission 178). An intermediate value of $750/acre is used here as suggested by Wange et al. (1974). Embodied energy cost of reclamation per ton is (0.00002 acres/ton)($750/acre)$(2.2 \times 10^6$ solar Cal/$) = 3.3×10^5 solar Cal/ton rock, or $(3.3 \times 10^5$ solar Cal/ton rock) (3.31 ton rock/ton fertilizer) = 1.1×10^6 solar Cal/ton fertilizer.

Sand tailings. Reclamation costs of sand tailings are given in terms of $/acre-ft. The amount of acre-ft in 3.31 tons of sand (total sand waste per ton fertilizer, see waste volume footnote below) = [(1 ton sand)$(10^6$ g/ton)/(1.4 g/cm^3)]/[$(2.832 \times 10^4$ cm^3)/ (ft^3)] = $(7.14 \times 10^5$ cm^3)/$(2.832 \times 10^4$ cm^3/ft^3) = 25.2 ft^3 in terms of acreft = (25.2 ft^3)/(43,560 ft^3/acre-ft) = 6×10^{-4} acre-ft/ton fertilizer. Dollar cost of reclamation is $63.76/acre-ft (Phosphate Land Reclamation Study Commission 1978). Embodied energy cost of sand reclamation is $(6 \times 10^{-4}$ acre-ft/ton)($63.76/acre-ft) $(2.2 \times 10^7$ solar Cal/$) = 8.4×10^5 solar Cal/ton fertilizer. Total reclamation costs (x 10^6 solar Cal/ton): Clay pond, 9.6; Spoil, 1.1; Sand tailings, 0.8; Total = 11.5. Total reclamation cost based on the annual production of fertilizer plants is $(11.5 \times 10^6$ solar Cal/ton)$(1.2 \times 10^6$ tons/yr) = 1.4×10^{13} solar Cal/yr.

APPENDIX VI
SPECIES LISTS USED IN SIMILARITY CALCULATIONS

Southern Mixed Hardwoods
(Quarterman and Keever 1962)

- *Fagus grandiflora*
- *Quercus alba*
- *Liquidambar styraciflua*
- *Quercus laurifolia*
- *Magnolia grandiflora*
- *Quercus nigra*
- *Carya tomentosa*
- *Carya glabra*
- *Pinus taeda*
- *Quercus falcata*
- *Nyssa sylvatica*
- *Ilex opaca*
- *Pinus glabra*
- *Acer barbatum*
- *Quercus michauxii*
- *Tilia* spp.
- *Carya pallida*
- *Fraxinus americana*
- *Ostrya virginiana*

Coastal Live Oak Hammock
(Laessle and Monk 1961)

- *Quercus virginiana*
- *Quercus laurifolia*
- *Carya glabra*
- *Ilex opaca*
- *Osmanthus americanus*
- *Sabal palmetto*
- *Magnolia grandiflora*
- *Persea borbonia*
- *Ilex vomitoria*
- *Juniperus silicicola*

South Florida Tropical Hammock
(Harper 1921)

- *Bursera simaruba*
- *Sabal palmetto*
- *Coccolbis laurifolia*
- *Quercus virginiana*
- *Sideroxylon foetidissimum*
- *Eugenia consufa*
- *Ficus* spp.
- *Persea borbonia*
- *Ichthyomethia piscipula*
- *Lysiloma bahamensis*

North-Central Florida Mixed
Hardwoods (Monk 1965)

- *Acer barbatum*
- *Acer rubrum*
- *Carpinus caroliniana*
- *Carya* spp.
- *Celtis laevigata*
- *Cornus florida*
- *Fraxinus* spp.
- *Ilex opaca*
- *Juniperus virginiana*
- *Liquidambar styraciflua*
- *Magnolia grandiflora*
- *Nyssa sylvatica*
- *Osmanthus americanus*
- *Ostrya virginiana*
- *Persea borbonia*
- *Pinus glabra*
- *Pinus taeda*

North-Central Florida Mesic
Hammock (Veno 1976)

- *Quercus virginiana*
- *Quercus hemisphaerica*
- *Quercus myrtifolia*
- *Quercus chapmanii*
- *Pinus palustris*
- *Magnolia grandiflora*
- *Vaccinium arboreum*
- *Osmanthus americana*
- *Lyonia ferruginea*
- *Carya glabra*
- *Liquidambar styraciflua*
- *Myrica cerifera*

Central Florida Sandy Hammock
(Sellards et al. 1915)

- *Quercus laurifolia*
- *Magnolia grandiflora*
- *Persea borbonia*
- *Quercus geminata*
- *Carya glabra*
- *Cornus florida*
- *Quercus virginiana*
- *Ilex opaca*
- *Liquidambar styraciflua*
- *Quercus nigra*

Appendix IV. (continued.)

Carya sp.
Ficus breuifolia
Swietenia mahogoni
Sapindus saponaria
Roystonea regia
Krugiodendron ferreum
Pinus clausa
Sabal palmetto
Ostra virginiana
Tilia sp.

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BIOGRAPHICAL SKETCH

Patrick Carl Kangas was born on April 28, 1952, in Cleveland, Ohio. He grew up in Welshfield, Ohio, about 30 miles east of Cleveland and attended and graduated from Burton High School. In September 1970 he entered Kent State University. During the summer of 1973 he attended the University of Oklahoma Biological Station on the Oklahoma-Texas border. After graduating from Kent State University in May 1974 with a Bachelor of Science degree in biology, he moved to Norman, Oklahoma, and entered the Botany Department of the University of Oklahoma. At Oklahoma he held assistantships in the Oklahoma Biological Survey and in the Science and Public Policy Program. His thesis work involved the application of ecological principles to an economic system (fast food restaurants). He left Oklahoma in August 1976 and entered the University of Florida at Gainesville. His master's thesis was completed in 1978, when he formally graduated from the University of Oklahoma with an interdisciplinary Master of Science in ecology. While at Florida he participated in many projects as a member of the Systems Ecology Group at the Center for Wetlands. He left Florida in August 1979 to take a position in the Biology Department at Eastern Michigan University in Ypsilanti, Michigan. His dissertation was completed in April 1983 when he formally graduated from the University of Florida with a Ph.D. in environmental engineering sciences.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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